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January 2000
NSRP 0556
N7-96-1

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

Development of Electromagnetic Acoustic Transducers (EMATS) for Surface/Volumetric Inspection of Welds

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

in cooperation with
Halter Marine Group, Inc.

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **JAN 2000**		2. REPORT TYPE **N/A**			3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The National Shipbuilding Research Program, Development of Electromagnetic Acoustic Transducers (EMATS) for Surface/Volumetric Inspection of Welds**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230-Design Integration Tools Bldg 192, Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR’S ACRONYM(S)
					11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **122**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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DEVELOPMENT OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS) FOR SURFACE/VOLUMETRIC INSPECTION OF WELDS

- FINAL REPORT -

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January 17, 2000

PREPARED FOR

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AND
NAVAL SURFACE WARFARE CENTER

HMGI PURCHASE ORDER NO. 2228
PROJECT NO. 7-96-1
MTI CONTRACT NO. CRD - 1355
R&DD PROJECT NO. 43549

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1.0 EXECUTIVE SUMMARY

This report summarizes the results of the National Shipbuilding Research Program (NSRP) Project 7-96-1, ElectroMagnetic Acoustic Transducers (EMATs) for Surface/Volumetric Inspection of Welds. Project 7-96-1 is a continuation of two earlier projects concerning shipyard application of EMATs for surface and volumetric weld inspection. An initial feasibility study (7-91-3) completed for the SP-7 Welding Panel in June, 1994 demonstrated laboratory feasibility for the use of EMAT generated surface waves to replace magnetic particle (MT) and/or liquid penetrant (PT) for surface inspection of welds. A subsequent project funded by Knolls Atomic Power Lab (KAPL) through General Dynamics - Electric Boat (EB) extended the EMAT technology by evaluating shear wave sensors for volumetric weld examination and included system evaluation in the shipyard, comparing the results to conventional inspection methods (MT, PT, ultrasonics (UT), and radiography (RT)).

The results of the shipyard evaluation of the surface wave test were positive, while the outcome of the shear wave (SV) investigation for volumetric weld inspection was somewhat inconclusive. These conclusions led to the proposing of additional EMAT evaluations to the SP-7 Welding Panel, resulting in Project 7-96-1, a two year program divided into two phases. Due to the inconclusive results of the diffraction-based approach for volumetric weld inspection, alternate methods of volumetric weld inspection were investigated, and the results of these studies are reported here.

Evaluation of the surface wave test is now complete, and the test should be considered ready for implementation by the various SP-7 member shipyards. McDermott Technology, Inc. can assist the shipyards in obtaining EMAT electronics, sensors and support, but the individual yards will need to determine their own requirements for system deployment. The diffraction-based test is capable of high speed scanning and detection of surface-breaking as well as subsurface flaws in structure type welds. The attenuation based test is suitable for even higher speed inspection and detection of surface-breaking and subsurface flaws in mechanized or automatic welds. In addition, the attenuation technique can be employed for extremely rapid surface inspection of painted base material.

In order to initiate the process of Navy approval for the EMAT inspection method, a meeting was held In Washington, D.C. in November, 1997 with two Navy shipyards (EB & Newport News Shipbuilding) and NAVSEA present. The purpose of the meeting was to determine the requirements for implementation of the surface wave test in Navy yards. NAVSEA indicated that it will be the responsibility of the shipyards to make their intentions known to NAVSEA and then to build their case for approval of the EMAT method for surface inspection of welds.

For volumetric testing the shipyard evaluations showed that the diffraction test had difficulty in discriminating between insignificant porosity and the ends of a significant flaw, e.g., lack of fusion (LOF), so it was discontinued. An investigation of volumetric inspection of welds was conducted with the sensor oriented normal to the weld axis, as is typical with conventional ultrasonic weld inspection. The fixed beam angle (approximately 35^0) of the shear vertical wave (SV - vertically polarized) causes this mode to be sensitive to weld root/crown geometrical reflectors, so this approach was also discontinued. The high strength steels typically used in ship hull construction were found to have sufficient magnetic properties for magnetostrictive generation of ultrasound. Magnetostrictive generation requires the use of a pulsed electromagnet. Although somewhat larger than a permanent magnet sensor, the pulsed magnet can still result in a portable system suitable for shipyard use.

Phased array technology was found to be the preferred approach for volumetric inspection of welds using EMATs. This technique has the potential for replacing radiography and conventional ultrasonic inspection of welds. Fully implemented, it has the potential to perform high-speed automated volumetric inspection of welds without the need for use of a couplant. The system would be very flexible allowing operation on different wall thickness components and different weld configurations with only software configuration changes.

A shear horizontal wave phased array EMAT system developed by McDermott Technology, Inc. was used to conduct the investigation. The results of the investigation indicated that the system was capable of electronically sweeping the focal spot and determining the through wall height of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”). The system was also capable of determining the length of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”). This approach to weld testing appears to be applicable to magnetic steel pipe diameters from less than 5 mm (2”) up to flat plate. The system was capable of detecting lack of root penetration defects in magnetic steel welds with excellent signal to background noise, due to the absence of mode conversion using the SH wave mode. Lack of fusion at the weld cap was readily detected with a surface skimming (90°) SH wave in a magnetic steel weld. A rapid drop in angle beam EMAT sensitivity with frequency for nonmagnetic high-resistivity metals makes it impractical to operate at frequencies high enough to provide adequate resolution for sizing the through wall height of weld defects in these metals with the present system. Positive test results were obtained for ship hull welds as well as piping welds using phased array EMATs.

EMAT technology has been making significant inroads into mainstream NDE. The high cost, large size, and complexity of EMAT instrumentation has been a limiting factor in the application of EMATs for field use. Most of the EMAT systems that are commercially available today are large systems developed for stationary installation in factories. Until
recently the components needed to implement small, lightweight, low-cost EMAT systems were not readily available.

Through a series of developments at McDermott Technology, the basic components for portable low-cost EMAT systems are now available. A top-level design of a portable EMAT system based on these developments has been conducted for application in shipyard inspections. This design provides a single lightweight integrated instrument for performing EMAT based inspections incorporating laptop PC based instrument control, data acquisition, and data processing, allowing full featured testing. These features include high-speed scanning, real time display of inspection results, and archiving of data for future reference. The use of a Laptop PC provides a low cost platform for the system that allows for ease of upgrade to take advantage of future improvements in PC performance. Modular design allows battery operation with the addition of a battery pack when using permanent magnet based EMATs, or a magnet pulser for use with pulsed magnet EMATs. An optional heads up display allows single operator inspections to be performed.

The results of these investigations are documented in this final report, which is a compilation of the four summary reports for the individual Tasks of Phase 1 and Phase 2 of NSRP Project 7-96-1.

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Keywords:

Weld Inspection
Ultrasonic Testing
Electromagnetic Acoustic Transducer (EMAT)
Phased Array
Shipyard

2.0 INTRODUCTION AND BACKGROUND

There is a need for improved weld inspection methods in ship fabrication yards. The currently recognized surface inspection method, Magnetic Particle or MT, can be slow (it is a static test), difficult to apply and interpret results, it is operator subjective, can damage the material due to arc strikes, and disposal of wastes is becoming more and more of a concern. The current volumetric tests, Ultrasonics (UT) and Radiography (RT), are relatively slow (UT & RT), subject to couplant limitations (UT), require post-test cleanup of couplant (UT), cause licensing and personnel safety concerns (RT) and, consequently, are expensive to use. ElectroMagnetic Acoustic Transducers (EMATs) can provide a high speed, dynamic inspection for both surface-breaking defects as well as volumetric flaws in a single scan along the weld bead. There is no post-test cleanup or disposal required, the data is easy to interpret, and the test can be performed at elevated or high temperatures immediately after the weld is completed. Shipyard application of surface/volumetric weld inspection using EMATs is being evaluated in order to improve current methodology used for the surface and volumetric inspection of structure type welds. It is intended to overcome difficulties in conventional MT and liquid penetrant (PT) for surface inspection of welds and UT/RT for volumetric inspection of welds, and ultimately provide a higher quality, lower cost weld inspection technique.

An EMAT generates and receives ultrasonic waves without using a couplant between the transducer and the material in which the sound waves are traveling, eliminating a source of error in ultrasonic flaw detection and enabling greater automation of nondestructive testing and measuring processes for production applications. The system also reduces the calibration requirements for flaw detection in welds.

This project involves the development of EMAT techniques for both surface and volumetric weld inspection, specifically for shipyard use. It is a continuation of earlier programs sponsored by the SP-7 Welding Panel of the National Shipbuilding Research Program and General Dynamics - Electric Boat Division (EB) through Knolls Atomic Power Lab (KAPL). The results of these earlier projects 1) indicated that EMATs are suitable as a replacement for the surface inspection of welds presently performed using MT/PT and 2) involved evaluation of shear wave sensors for volumetric weld examination and system evaluation in the shipyards, comparing the results to conventional inspection methods (MT, PT, UT, and RT). The results of the KAPL-sponsored laboratory and shipyard evaluations of the EMAT surface inspection technique were excellent with the following conclusions:

- The EMAT surface wave test based on diffraction provides a good surface inspection technique for detection of surface-breaking/near-surface flaws in typical shipyard welds in the as-welded condition (no surface prep).

- The attenuation technique for surface inspection is useful for high speed scanning of mechanized welds. It is even more suitable for surface inspection of large areas of base metal at extremely high speeds. The test can even be used for painted surfaces.

- EMAT system portability/practicality is favorable, with the KAPL trip report stating that the EMAT system "was judged to be compact and practical for shipyard applications".

- Set-up times and test speeds were excellent, with the KAPL trip report stating "system set-up required less than one hour and the EMAT volumetric inspection speed was judged to be comparable to manual ultrasonic testing".

- The diffracted surface wave test speed is significantly faster than MT. The EMAT surface wave test was used to scan and mark indications on a 42' web-to-flange T-weld segment in seven minutes. It is estimated that this length of weld would have required approximately 100 minutes to inspect with MT.

The results of the KAPL-sponsored laboratory and shipyard evaluations of the volumetric technique (vertically polarized (SV) shear wave) were somewhat inconclusive, however, with the following conclusions:

- The EMAT angle beam shear wave (SV) test based on diffraction provides a good volumetric inspection technique for detection of subsurface flaws in welded thick section plate. The diffraction-based test for volumetric inspection is intended for rapid screening/defect detection only and not flaw sizing, i.e., the focused SV shear wave sensor results in a line focus which cannot provide through-wall depth information.

- Volumetric test evaluations indicated that the diffraction test has difficulty in discriminating between insignificant porosity and the ends of a lack of fusion (LOF) defect. The advantage of the diffraction test (its ability to eliminate responses to long, linear anomalies such as the weld root and crown) apparently causes it to have difficulty in discriminating between porosity and LOF.

These concerns were brought to the attention of the SP-7 panel members at the January, 1997 meeting in Miami, FL in order to redirect the project workscope. In light of the positive as well as negative results obtained in the shipyard investigations to date and the manner in which they impact the workscope of the current project, the original Statement of Work was revised with concurrence by the SP-7 panel members at the January, 1997 Miami meeting. The revised workscope provided for the evaluation of phased array EMATs for volumetric weld inspection and the investigation into improving the EMAT electronics for field use. The redirected workscope is given in the following paragraph.

Work on the project has progressed as follows:

1) The project has been divided into two phases with multiple tasks:

PHASE 1 (1997-1998):

Task 1: Procure Representative Welded Samples
Task 2: Complete Volumetric Test Investigation (drop diffraction approach due to insufficient flaw discrimination)
  Subtask 1: Evaluate multi-element SV shear wave approach (improved time resolution)
  Subtask 2: Evaluate SH shear waves at alternate beam angles
  Subtask 3: Investigate the use of phased array technology
Task 3: Refine Surface Wave Test
  Subtask 1: Evaluation on complex geometries
  Subtask 2: Evaluate attenuation technique for painted base material
  Subtask 3: Establish hardened sensor design
Task 4: Reporting and Administration

PHASE 2 (1998-1999):

Task 1: Acquire Representative Samples
Task 2: Investigate Use of Phased Array for Circumferential Piping Welds (Carbon steel, Austenitic SS, Inconel, Cu/Ni, Ni/Cu)
Task 3: Establish EMAT Instrumentation Design for Maximum Portability

Tasks 1 and 2 of Phase 1 were completed and are the subject of a previous summary report, “Completion of Volumetric Test Investigations”. Highlights of this work are as follows:

- All EMAT evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

- In an earlier project funded by KAPL/EB, the results of shipyard evaluations of a diffraction-based volumetric test were indefinite because the test was found to be too sensitive to slag inclusions/scattered porosity. Since the diffraction test was seen to have difficulty in discriminating between insignificant porosity and the ends of a significant flaw, e.g., LOF, the decision was made to discontinue further development of the diffraction approach.

- The over sensitivity to scattered porosity was found to be caused by the use of a focused sensor.

- The initial non diffraction-based volumetric evaluations were conducted using a permanent magnet/unfocused 2MHz SV sensor, resulting in insufficient S/N for LOF.

However, the unfocused sensor did minimize sensitivity to insignificant porosity.

- Subsequent 2MHz SV work relied on the use of a pulsed magnet and unfocused sensor with the following results:

  - Normal incidence - minimal response to porosity
  - Good system portability
  - Good S/N for LOF (10:1)
  - Fixed 32° beam angle - too sensitive to weld root/crown
  - Poor correlation with NAVSEA UT/RT results on NSWC test plates

- The magnetic properties of the high strength steels used in ship construction were found to be conducive to magnetostrictive generation of ultrasound. Magnetostriction enables the use of SH waves to perform the volumetric inspection of welds. The use of a pulsed magnet and unfocused 1.2MHz SH sensor @ 60^0 beam angle (parallel field) provided the following results:

  - Normal incidence - minimal response to porosity
  - Good system portability
  - Good S/N for LOF (>10:1)
  - Minimal response to scattered porosity & weld root/crown
  - Good correlation with NAVSEA UT/RT results on NSWC test plates

- Frequency scanned SH waves can improve volumetric weld inspection.

  - Beam can be swept (0-90°) by small changes in test frequency
  - Covers complete weld volume, eliminating raster probe motion
  - Good correlation with NAVSEA UT/RT results on NSWC test plates
  - Less expensive than phased array, but much slower

- Phased array technology permits simultaneous surface/volumetric inspection of welds.

- Phased array technology provides not only the ability to detect flaws, but also allows complete weld characterization, i.e., it provides the capability to distinguish between significant flaws (LOF) and insignificant defects (scattered porosity).

- The incorporation of phased array technology offers enhanced performance capabilities for EMATs for weld inspection applications. Advantages include:

  - Excellent time-of-flight resolution for accurate velocity measurements
  - Removal of couplant influences for more accurate measurements (e.g., attenuation)
  - Generation of broadband signals more conducive to frequency analysis
  - High degree of signal reproducibility (derived from lack of couplant variations and reproducible transducer design and control) to enable application of

feature extraction and pattern recognition algorithms or neural networks for classification of degradation

- Enhanced scanning capability with limited probe movement requirements for applications involving complex geometries
- Software control of focal spot size, depth, and angle, allowing for rapid scanning of many configurations
- Ability to easily utilize any of the wave modes, including the SH wave mode, which is difficult to apply in a scanning mode with conventional UT

Task 3 of Phase 1 has been completed and is the subject of a previous summary report "Refinement of Surface Examination Methods". Highlights of this work are as follows:

- Two methods, one based on diffraction and the other on attenuation, have been developed for surface inspection of welds. Both tests can be used for rapid and reliable subsurface and surface-breaking flaw detection in structure type welds.

- All EMAT evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

- Zig-Zag (Attenuation Technique)

    - 2MHz surface waves
    - 1/2" x 1/4"permanent magnets (NdFeB)/unfocused coils
    - Excellent high speed test of mechanized welds/base metal
    - Not suitable for rough welds or complex geometries
    - Operates on painted surfaces (up to 15 mils thick)
    - Capable of detecting surface-breaking and subsurface flaws at all orientations

- Diffraction Technique

    - EB supplied welded mockup with complex geometries (corners, tees)
    - 0.125"L X 0.060"D flaws in various locations/orientations
    - 1MHz focused surface waves/1 inch cube NdFeB permanent magnet sensor
    - A superior wear face material has been identified - Havar[7] (Co/Ni/Cr alloy)
    - All flaws were detected with good S/N except in corner. Corner flaws are not detectable due to the energy reflected from corner geometry back to sensor.
    - Best results on butt welds (S/N > 20:1)
    - Good results on "rough" fillet welds (S/N >15:1)

Tasks 1 and 2 of Phase 2 have been completed and are the subject of a previous summary report, "Phased Array EMATs for Circumferential Piping Welds". Highlights of that work are as follows:

- The phased array system was capable of focusing the SH wave beam to a focal spot of approximately 2 mm (.080”) by 2 mm (.080”) in magnetic steels.

- The system was capable of electronically sweeping the focal spot and determining the through wall height of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”).

- The system was capable of determining the circumferential length of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”) by moving the focused beam testhead along the weld and monitoring the defect signal as a function of position.

- This approach to weld testing appears to be applicable to magnetic steel pipe diameters from less than 5 mm (2”) up to flat plate.

- The system was capable of detecting lack of root penetration defects in magnetic steel welds with excellent signal to background noise, due to the absence of mode conversion with the SH wave mode.

- Lack of fusion at the weld cap was readily detected with a surface skimming (90°) SH wave in a magnetic steel weld using the phased array EMAT system.

- A rapid drop in angle beam EMAT sensitivity with frequency for nonmagnetic high-resistivity metals makes it impractical to operate at frequencies high enough to provide adequate resolution for sizing the through wall height of weld defects in these metals with the present system.

Task 3 of Phase 2 has been completed and is the subject of a previous summary report “EMAT Instrumentation Design for Maximum Portability”. Through a series of developments at McDermott Technology, the basic components for portable low-cost EMAT systems are now available. A top-level design of a portable EMAT system based on these developments has been conducted for application in shipyard inspections. This design provides a single lightweight integrated instrument for performing EMAT based inspections incorporating laptop PC based instrument control, data acquisition, and data processing, allowing full featured testing. These features include:

- A single lightweight integrated instrument for performing EMAT based inspections.

- Laptop PC based instrument control, data acquisition, and data processing allow full featured testing. These features include high-speed scanning, real time display of inspection results, and archiving of data for future reference.

- The use of a Laptop PC provides a low cost platform for the system that allows for ease of upgrade to take advantage of future improvements in PC performance.

- Modular design allows a battery operation with the addition of a battery pack when using permanent magnet based EMATs, or a magnet pulser for use with pulsed magnet EMATs.

- An optional heads up display allows single operator inspections to be performed.

The results of these investigations are documented in this final report, which is a compilation of the four summary reports for the individual Tasks of Phase 1 and Phase 2 of NSRP Project 7-96-1.

3.0 COMPLETE VOLUMETRIC TEST INVESTIGATION

DEVELOPMENT OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS) FOR SURFACE/VOLUMETRIC INSPECTION OF WELDS

- FINAL SUMMARY REPORT -

COMPLETETION OF VOLUMETRIC TEST INVESTIGATIONS

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HMGI PURCHASE ORDER NO. 2228
PROJECT NO. 7-96-1
MTI CONTRACT NO. CRD - 1355

3.1 SUMMARY

This report summarizes the results of a specific task, *Completion of Volumetric Test Investigations*, in National Shipbuilding Research Program (NSRP) Project 7-96-1, "ElectroMagnetic Acoustic Transducers (EMATs) for Surface/Volumetric Inspection of Welds." Project 7-96-1 is a continuation of two earlier projects concerning shipyard application of EMATs for surface and volumetric weld inspection. An initial feasibility study (7-91-3) completed for the SP-7 Welding Panel in June, 1994 demonstrated laboratory feasibility for the use of EMAT generated surface waves to replace magnetic particle (MT) and/or liquid penetrant (PT) for surface inspection of welds. A subsequent project funded by Knolls Atomic Power Lab (KAPL) through General Dynamics - Electric Boat (EB) extended the EMAT technology by evaluating shear wave sensors for volumetric weld examination and included system evaluation in the shipyard, comparing the results to conventional inspection methods (MT, PT, ultrasonics (UT), and radiography (RT)). The results of the shipyard evaluation of the surface wave test were positive, while the outcome of the shear wave investigation for volumetric weld inspection was somewhat inconclusive. These conclusions led to the proposing of additional EMAT evaluations to the SP-7 Welding Panel, resulting in Project 7-96-1, a two year program divided into two phases. This report describes the results of one of two tasks in Phase 1.

Due to the inconclusive results of the diffraction-based approach for volumetric weld inspection, alternate methods of volumetric weld inspection were investigated, and the results of these studies are reported here. The shipyard evaluations showed that the diffraction test had difficulty in discriminating between insignificant porosity and the ends of a significant flaw, e.g., lack of fusion (LOF), so it has been discontinued, and volumetric inspection of welds will now be conducted with the sensor oriented normal to the weld axis, typical with conventional ultrasonic weld inspection. The fixed beam angle of the shear vertical wave (SV - vertically polarized) causes this mode to be sensitive to weld root/crown geometrical reflectors, so this approach was also discontinued. The shipyard evaluations showed that a focused sensor was overly sensitive to slag inclusions and scattered porosity, but subsequent testing with an unfocused transducer utilizing a permanent magnet resulted in insufficient signal-to-noise ratio for LOF. The high strength steels typically used in ship construction were found to have sufficient magnetic properties for magnetostrictive generation of ultrasound. Magnetostrictive generation requires the use of a pulsed electromagnet. Although somewhat larger than a permanent magnet sensor, the pulsed magnet can still result in a portable system suitable for shipyard use.

Phased array technology was found to be the preferred approach for volumetric inspection of welds. In addition, the phased array methodology can be used to perform a simultaneous surface and volumetric weld inspection. McDermott Technology, Inc. (MTI)
is prepared to assist the shipyards in obtaining EMAT electronics, sensors and support, as well as in determining their requirements for system deployment.

3.2 INTRODUCTION / BACKGROUND

A comprehensive introduction and background for the project is given at the beginning of this final report.

3.3 COMPLETION OF VOLUMETRIC TEST INVESTIGATION

The results of the shipyard evaluations of the ***diffraction-based*** volumetric test were indefinite because the test was found to be too sensitive to insignificant indications caused by slag inclusions/scattered porosity. Since the diffraction test was seen to have difficulty in discriminating between insignificant porosity and the ends of a significant flaw, e.g., lack of fusion (LOF), the decision was made to discontinue further development of the diffraction approach. The primary advantage of the diffraction technique, its ability to eliminate the ultrasonic responses from extraneous variables such as geometrical reflectors (root/crown/toe), causes it to have difficulty in discriminating between porosity and long, linear anomalies such as LOF. The diffraction method also has difficulty in determining the length of indications as well as through-wall depth information. For these reasons, alternate methods (not based on diffraction) of volumetric weld inspection were investigated, and the results of these studies are reported in the following sections.

Welded test plates were obtained from the Naval Surface Warfare Center - Carderock Division (NSWC) to be used for the volumetric test development. These 2'x2'x12" thick HY-80 plates (designated A4, A10, A17, and A18) contained a full length butt weld (SMAW, GMAW, and Auto GMAW) with well-documented defect locations and had been designed/fabricated for an earlier NAVSEA project involving evaluation of conventional ultrasonics as a replacement for radiography. A photograph of plate number A17 is seen in Figure 1. Regarding the documentation of the implanted weld defects, a typical flaw map is shown in Figures 2a and 2b. The particular map depicted in these figures is for plate number A4. A plate is described in two maps because the 24" wide plate was divided into two (2) 12" sections, with each section depicted on a separate map. The map shows the flaw locations along the weld axis as well as through-wall position or depth, flaw length, signal amplitude of the UT indication (from the previous NAVSEA UT in lieu of RT project), discontinuity type, and UT probability of detection (POD). It should be noted that all evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

3.3.1 Vertically Polarized Shear (SV) Wave Evaluations

The previous project funded by EB/KAPL found the focused SV sensor to be too sensitive to scattered porosity, a flaw considered by the shipyard to be insignificant, non-detrimental to weld integrity. An unfocused sensor minimized response to this inconsequential porosity, but the permanent magnet/unfocused 2MHz SV sensor was found to provide insufficient signal to noise (S/N) for reliable detection of a significant weld flaw such as LOF. The permanent magnet sensor had been a goal from a system portability standpoint, but was discontinued as a result of the inadequate S/N. Next, investigations determined that the magnetic properties of HY-80 were suitable for magnetostrictive generation of ultrasound, requiring the use of a pulsed magnet sensor. A pulsed magnet/unfocused 2MHz SV sensor was used at normal incidence to the weld, i.e., sensor and resultant beam oriented normal to weld axis, resulting in minimal response to insignificant porosity, and good S/N (10:1) for detection of LOF. Although there were initial concerns about the portability of a pulsed magnet sensor and associated power supply/switching circuitry, the approach was found to maintain system portability because the sensor is approximately the same size as a conventional piezoelectric sensor/wedge combination with a 1"element (typically used in shipyard weld inspection). However, the SV approach was abandoned when the test results showed there to be inadequate correlation with NSWC plate flaw maps. In addition, the fixed 32^{O} beam angle for the SV shear wave approach was too sensitive to the weld root/crown, resulting in numerous extraneous signals which confused and hindered data interpretation.

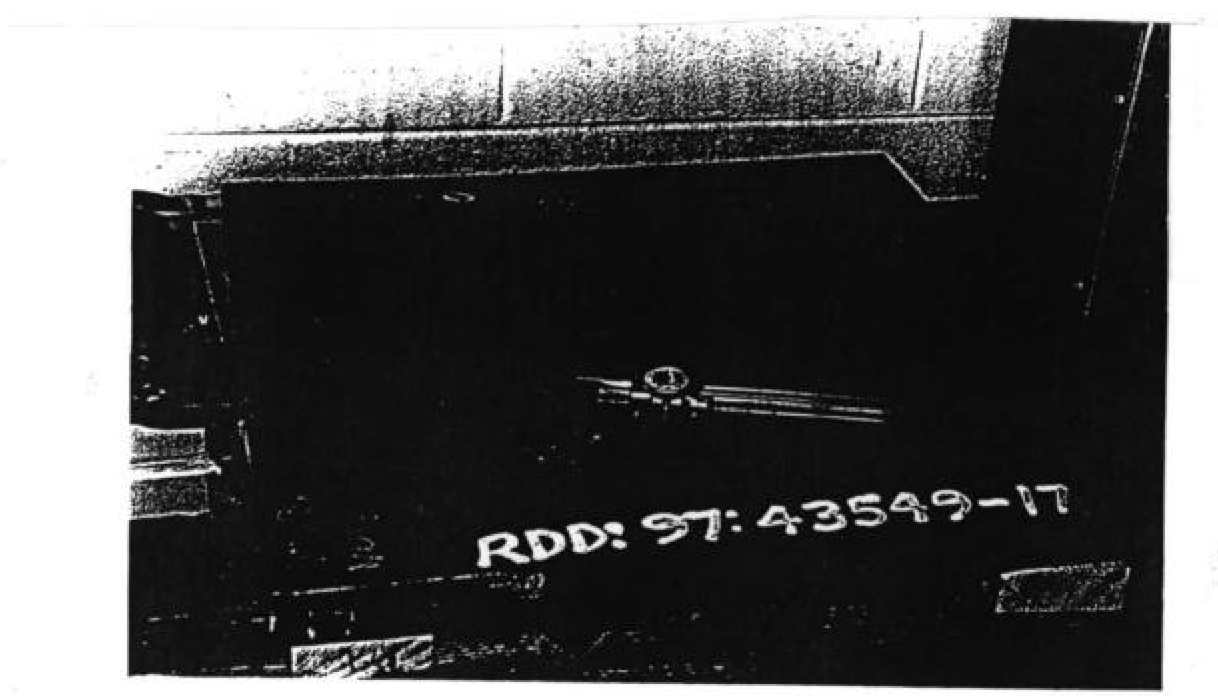


FIGURE 3-1 NSWC-Supplied Test Plate A17 Containing Known Volumetric Flaws

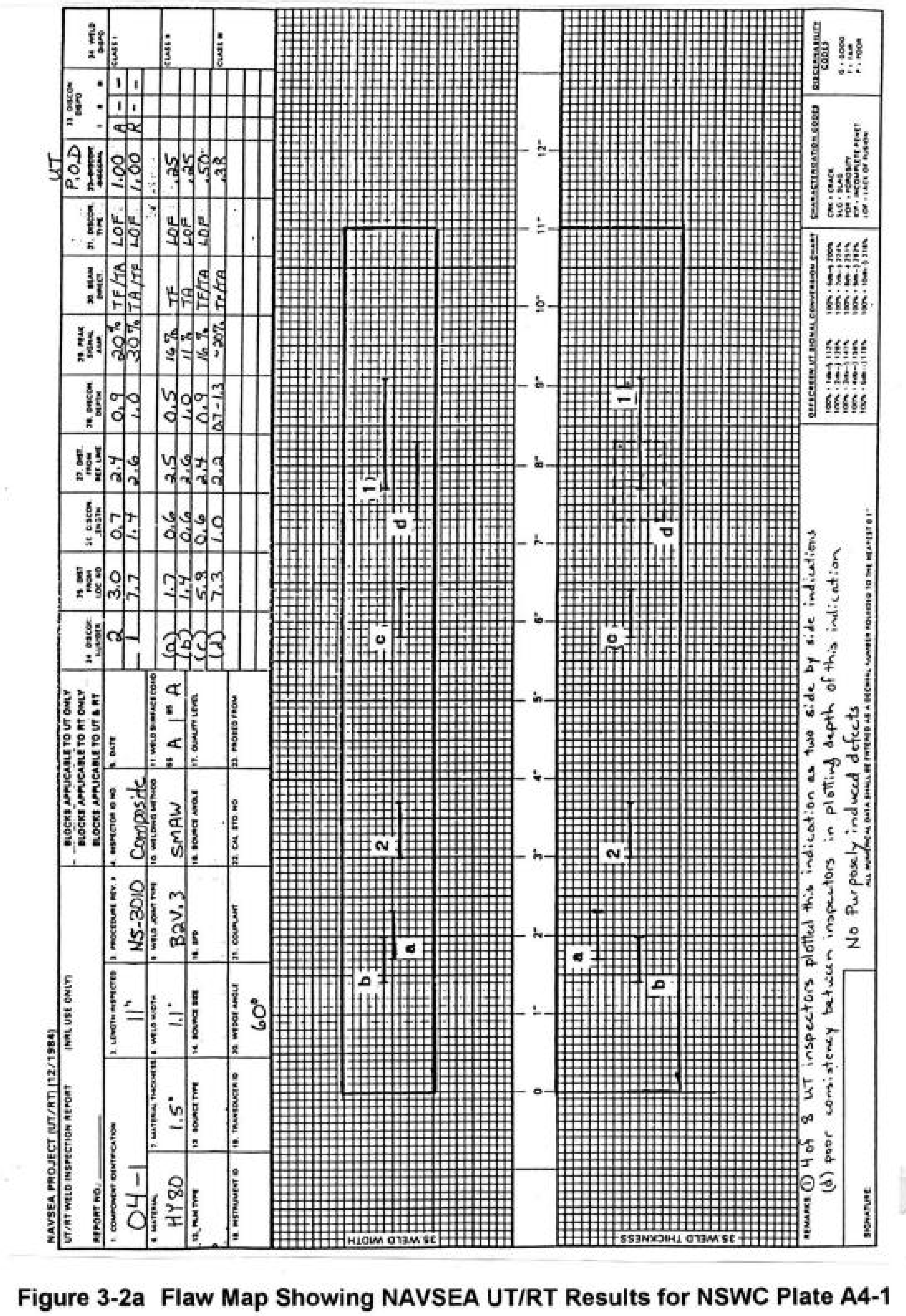


Figure 3-2a Flaw Map Showing NAVSEA UT/RT Results for NSWC Plate A4-1

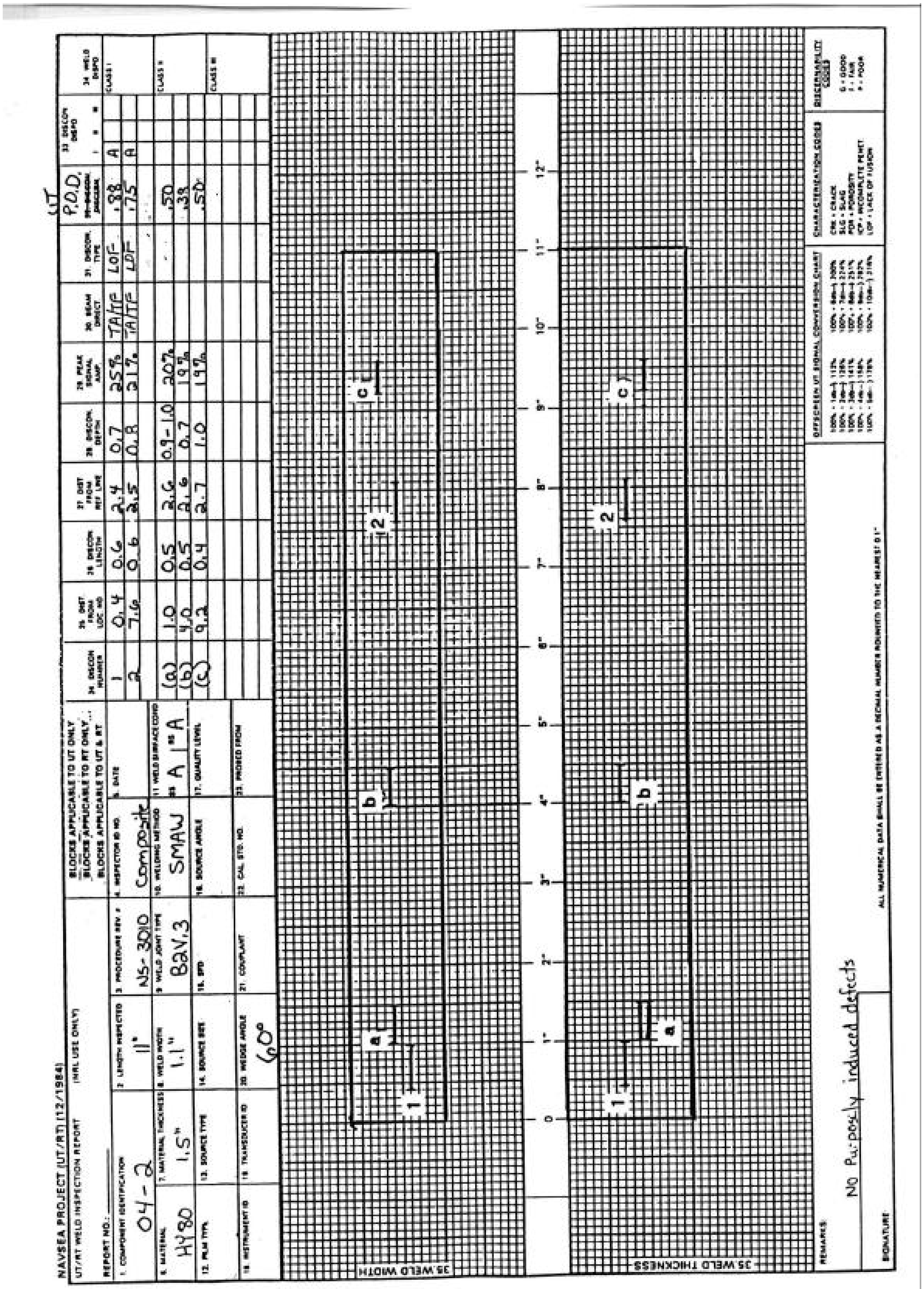


Figure 3-2b Flaw Map Showing NAVSEA UT/RT Results for NSWC Plate A4-2

3.3.2 Horizontally Polarized Shear (SH) Wave Evaluations

EMATs excel in the generation of shear horizontal (SH) wave modes. A single wire element in a SH wave EMAT generates SH waves with equal amplitude for all beam angles. SH waves reflect from planar reflectors with equal amplitude at all angles of incidence without mode conversion. These advantages allow EMAT-generated SH wave ultrasonic beams to be used over a larger range of angles than conventional ultrasonic systems. Thus, in applications where the inspection could benefit from concentration on the SH mode (e.g., recent studies in ultrasonics for stress measurement have shown improvement in performance from capitalizing on the benefits derivable from the SH mode), the selection of EMATs could be beneficial. EMATs operating in an SH mode thus allow for the benefits of SH wave testing to accrue for weld inspection (including austenitic material) as well as automated applications.

After determining that the magnetic properties of the HY-80 material were amenable to magnetostrictive generation of ultrasound, a pulsed magnet/unfocused 1.2MHz SH sensor (parallel field, i.e., direction of the applied magnetic field is parallel to the radio frequency (RF) coil windings) was used to examine the weld of the NSWC plates. In order to interrogate the weld normal to the prep angle, a beam angle of 60 (measured from vertical) was selected. As stated earlier, one of the many advantages of the SH mode is that the beam angle is variable from 0-90 simply by making small changes in test frequency. The testing results showed that at normal incidence, i.e., sensor and resultant beam oriented normal to weld axis, there was minimal response to randomly distributed porosity. In addition, the SH approach maintains system portability, provides excellent S/N for LOF (>10:1), results in minimal response to both porosity and weld root/crown. Finally, the technique was found to result in good correlation with NSWC UT/RT plate flaw map. A C-Scan presentation of the results of the SH testing on NSWC plate A4 is seen in Figure 3. The C-Scan, constructed by raster scanning the SH sensor parallel to the weld in incremental fashion, can be compared to the flaw maps of plate A4 seen in Figures 2a and 2b. Figure 4 depicts the layout of the two-page flaw map, and the results of the C-Scan can be seen to correspond well to the NAVSEA results. The positive results of the SH testing served to lay the groundwork for the subsequent phased array testing, the description and results of which follow.

3.3.3 Investigate Use of Phased Array Technology

Ultrasonic examinations based on phased array EMATs offer the potential to provide rapid, precise characterization of degradation in materials. Phased array ultrasonic testing utilizes multi-element probes to which precise time delays are applied to the signals from each individual element, both in transmission and reception, to allow dynamic control of the beam angle, focal point, and focal width. Commercially available phased array systems are capable of transmitting and receiving at rates of up to 20,000 times per second and using up to 1,024 different programmable beam characteristics. The multi-element probes can either be of the conventional piezoelectric type or EMAT type. The integration of phased array electronics with custom designed EMAT probes can provide unique advantages for materials characterizations including shipyard weld inspection.

Current and developing needs within the shipyard community include simultaneous surface and volumetric weld inspection, including flaw characterization. To meet these needs, the manner in which NDE methods have traditionally been applied will need to be re-evaluated in light of the new and demanding requirements. For ultrasonic testing, it is envisioned that higher sensitivity, greater signal control, and enhanced reproducibility will be required to enable the detection of subtle changes in acoustic profiles as a result of materials properties changes during degradation. It is envisioned that the same proven enhanced capabilities offered by phased array operated EMATs for flaw detection could provide enhanced ultrasonic approaches to materials characterization needs (e.g., sectorial scanning capability, higher time resolution, focusing control).

Phased array ultrasonic testing is an area of recent NDE development that utilizes a multi-element probe for enhanced ultrasonic performance. By applying precise time delays to both transmitted and received signals from each individual element, it is possible to control the ultrasonic characteristics of the beam. Using this technique, the beam angle, focal point, and focal width can be dynamically adjusted. Thus, electronically controlled beam scanning of a component is enabled. A desired inspection sequence is configured by specifying which elements of the array are to be used and the desired focal point or beam angle. Software then calculates the required parameters and downloads them to the phased array instrument. A single RF signal comprises the output of a phased array device. This RF signal can be utilized in the same manner as conventional UT for viewing and/or signal processing.

Phased array technology has, for a number of years, been used extensively in medical ultrasonics (e.g., the well-known "sonograms" and "echocardiograms"). Until recently, these systems have been too bulky and expensive for general application in NDE primarily due to the electronic hardware required. Recent developments in electronics have allowed the size and cost of these systems to drop to the point of being economically attractive for specialized NDE use. This trend can be expected to continue, resulting in more widespread use of phased array systems for NDE in the near future.

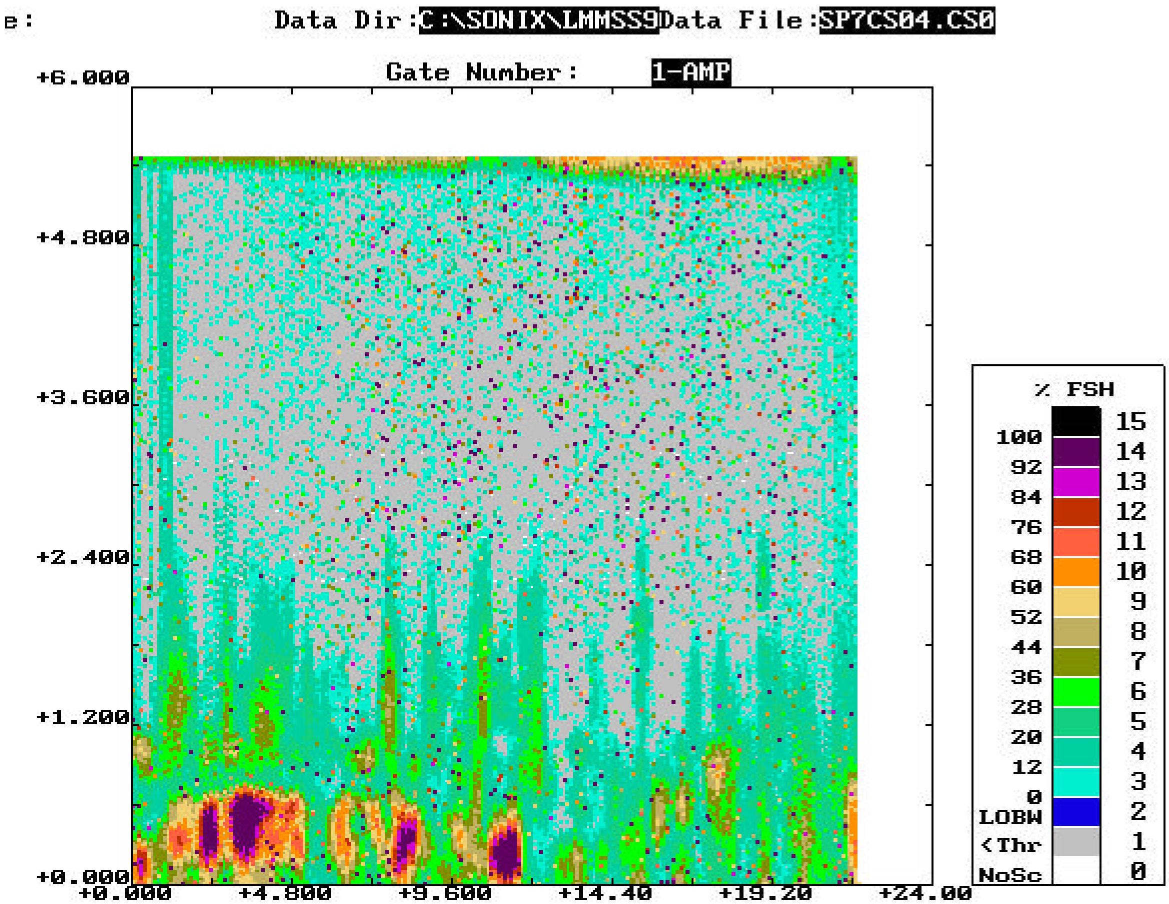
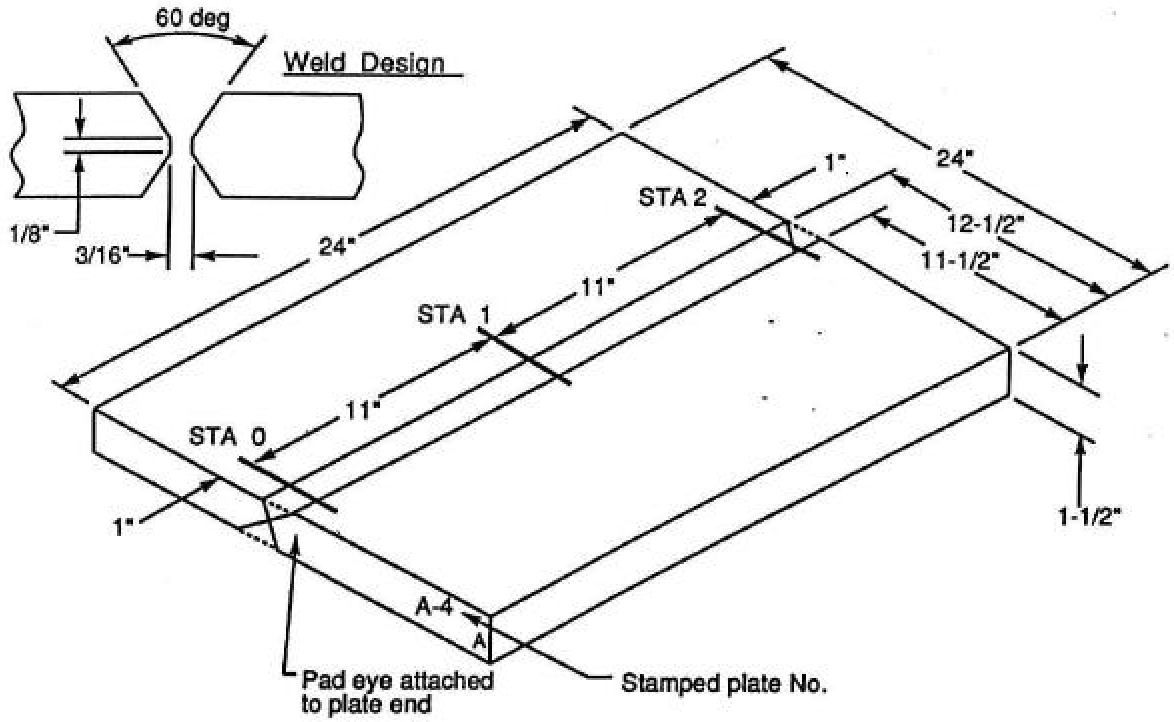


Figure 3-3 C-Scan of EMAT SH Wave Testing of NSWC Plate A4 (Weld Axis Coincides with Bottom of Printout)

Test plates A-4, A-10, A-17 and A-18 are 24" x 24" x 1.5" containing one full length butt weld. Weld design and inspection layout are shown below:



Notes to Inspection reports:

- UT was performed by 8 inspectors per NAVSEA 0900-LP-006-3010.
- UT P.O.D. = UT probability of detection.
- Numbered discontinuities are considered "significant". (Detected by 5 of 8 inspectors by either RT or UT). Lettered discontinuities are not significant (i.e. random detections by less than 5 of 8 by any method)
- RT was performed using 6 techniques; X-rays, iridium 192 and Cobalt 60, using both Kodak AA and M films. Each film was read by 8 film viewers.
- Component identification is as follows: XX-Y.
  XX = Plate No. (1 through 18), Y = 1 for Station 0-1, Y = 2 for Station 1-2.
- Accept/Reject criteria is based on UT per NAVSEA 0900-LP-006-3010.

Figure 3-4 Weld Design and Inspection Layout of NSWC-Supplied UT/RT Plates

3.3.3.1 Advantages of Phased Array EMATs for Weld Characterization

The inherent advantages of EMATs for certain ultrasonic applications have long been acknowledged within the NDE community. A basic difference between the EMAT and the conventional piezoelectric approach, that of operation without an acoustic couplant, has been one of its foremost advantages. Without the couplant requirement, high temperature and/or automated ultrasonic scans become easily achievable. When subtle changes in waveform characteristics are required to be detected (e.g., in pattern recognition applications for material characterizations), the lack of the effect of couplant variations on waveform characteristics is welcomed. Search unit reproducibility should also be mentioned as an advantage of EMATs over conventional UT transducers, adding to their preferred applicability in instances where waveform feature extraction details are required for intelligent signal processing.

Other advantages can result from the utilization of EMAT techniques. As previously discussed, EMATs excel in the generation of the SH wave mode. The SH wave EMAT generates sound with equal amplitude for all beam angles. SH waves reflect from planar reflectors with equal amplitude at all angles of incidence without mode conversion. These advantages allow EMAT-generated SH wave ultrasonic beams to be used over a larger range of angles than conventional ultrasonic systems. Thus, in applications where the inspection could benefit from concentration on the SH mode, the selection of EMATs could be beneficial.

Traditionally, there are certain disadvantages of EMATs over conventional UT applications. These potential disadvantages should be evaluated prior to EMAT selection for a given application. Foremost is the decrease in achievable S/N due to the poor coupling efficiency. A close second is the requirement for long RF tone bursts to generate focused wavefronts, which in turn is detrimental for applications where accurate time-of-flight measurements are necessary (e.g., accurate velocity measurements). EMAT applications can give rise to errors in time measurement of from 5-10 times that of conventional UT.

MTI has reaped advantages from applying phased array technology to EMATs to overcome their inherent disadvantages. Through precise timing of successive EMAT element pulsing, advantage has been made of the fact that short duration bursts can be utilized to generate highly focused wavefronts. Thus, EMAT signals more resemble spike pulses to which more precise time measurement is enabled.

Additional benefits are derivable from phased array applications of EMATs. Broadband acoustic signals result from the short time domain transmitted pulses; broadband signals are imperative for frequency analysis signal processing. The probe becomes a multi-functional device whereby multiple wave modes and beam steering enables wide range inspection. Dynamic adjustment of beam angle, focal point, and focal width is enabled through electronic control. Volume scanning becomes easier. Basically, the phased array EMAT approach combines the advantages of wide beam and focused beam ultrasonics into the same probe and further allows the inspector to reap the advantages of EMATs without forsaking the performance of conventional UT.

3.3.3.2 General Principle of Operation for Phased Array Technology

Angle beam, surface wave, and Lamb wave EMATs are phased array devices. The beam steering and beam width of angle beam EMATs are determined by phased array principles. Since phased array electronics have not been economically viable until recently, EMATs have traditionally been operated by connecting all the elements together and driving them with a long RF tone burst, such that each element will excite an ultrasonic wave that will be in “phase” with the waves launched by all other elements at a particular beam angle or focal point. A long RF tone burst is required in order for the waves from all the elements to be in phase at a particular beam angle or focal point. While adequate for many applications, the long RF tone bursts result in poor time-of-flight resolution. The error in determining the position of a reflector from time-of-flight measurements for a traditional angle beam EMAT is typically 5 to 10 times greater than for conventional ultrasonics. The use of phased array electronics, in which time delays are set individually for each element, allows short RF tone bursts to be used, resulting in time-of-flight resolution more in line with conventional ultrasonic testing. EMAT phased array systems have all the advantages of conventional ultrasonic phased array systems such as electronically controlled beam angle, focus point, focal width, and beam scanning. Finally, since EMATs have much lower transduction efficiency than conventional ultrasonics, the use of multiple individually driven elements, which combine to form the transmitted wave, results in substantially improved signal-to-noise ratio.

3.3.3.2.1 Beam Focusing

Figure 5 shows a diagram of a multi-element EMAT transducer for phased array operation. Through precise timing and consequent phasing of transmitted pulses from each independent element, the resulting generated wavefronts combine into a highly focussed beam. The same procedure enables software control of the focal depth. Figure 6 depicts this phenomenon. Upon reception, precise time delays are consequently applied to the individual element responses (Figure 7), and the summation of all elements taken. Figure 8 gives an indication of the achievable accuracy in time-of-flight measurement and characterization (i.e., size and orientation) of a phased array EMAT system. Shown are those points within 6 dB of the maximum received amplitude derived from electronically scanning axially along a pipe with a 0.120 inch flat bottom hole (FBH) simulating a 30 degree weld bevel. The actual FBH is represented by the sloid rectangle, with the coordinates of 4 separate reflections plotted in relation (from time-of-flight measurements) to the FBH. Each data point corresponds to an axial scan of one EMAT element (0.0825 inch). For this example, 60 degree angled beams (with 0.120 inch focal spot size) were reflected from the inside surface of a 0.720-inch wall pipe.

3.3.3.2.2 Scanning

Figure 9 shows the methodology by which calculated firings of the EMAT elements can be utilized to steer the ultrasonic beam. Angles from 0 to 90 degrees are achievable, enabling whole-component scanning of complex geometries, and for materials characterization, minimizing the influences from anisotropic materials, e.g. austenitic stainless steels and inconels.

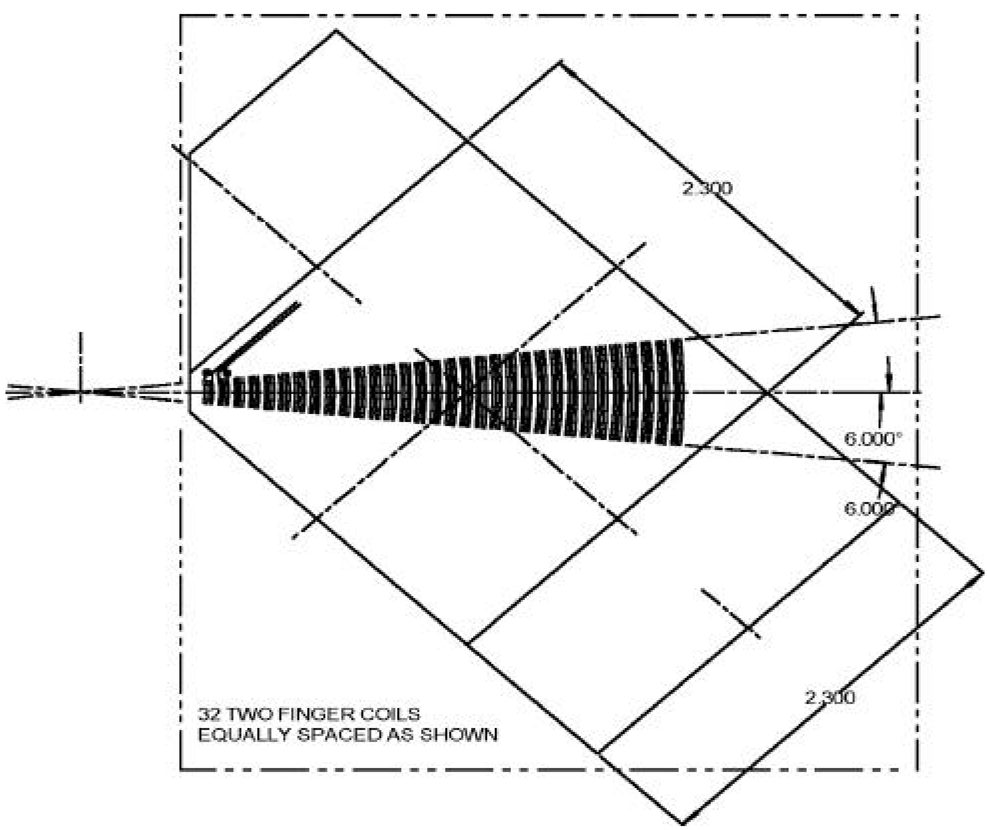


Figure 3-5 Multi-Element Phased Array EMAT Coil Used for Inspection of NSWC-Supplied Plate Weld

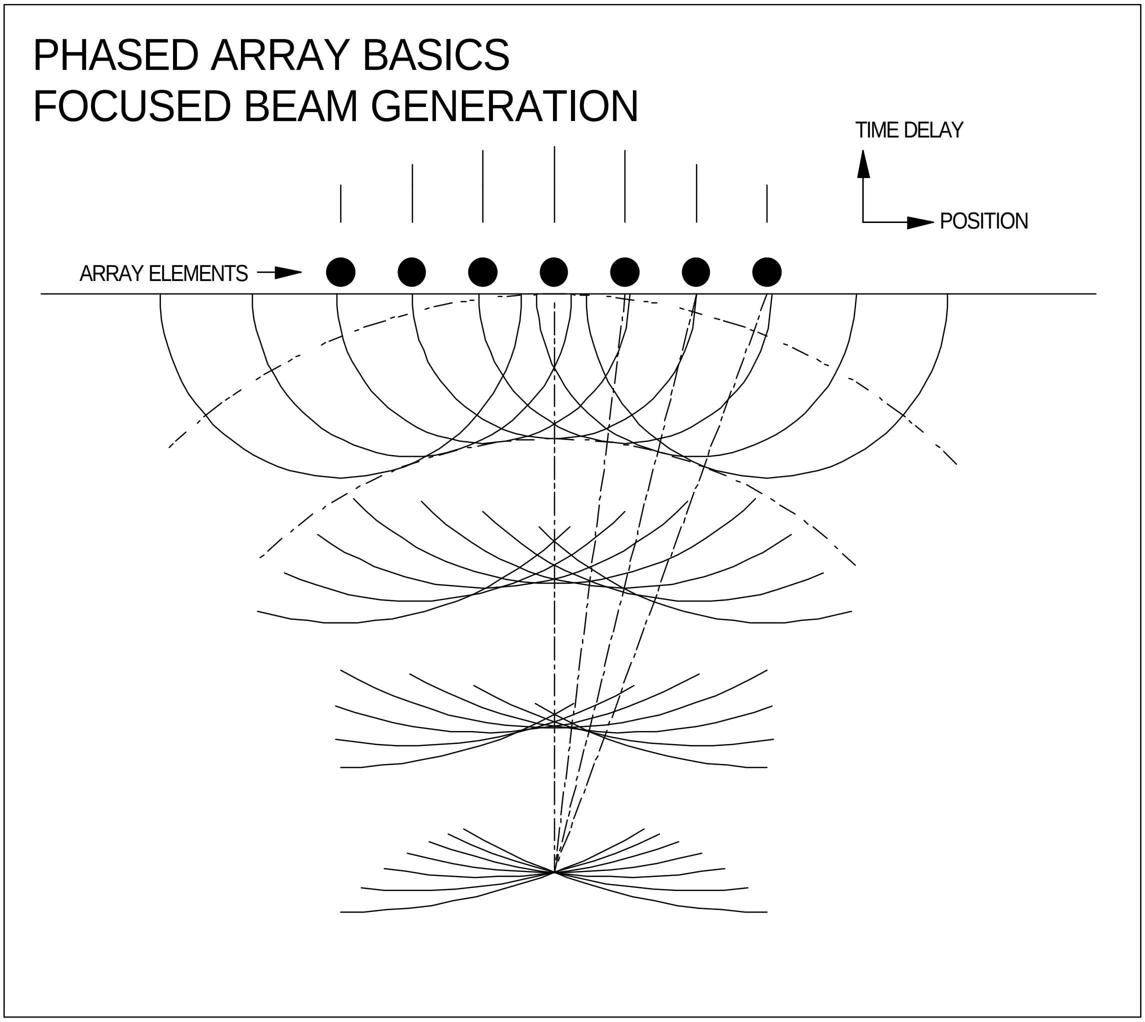


Figure 3-6 Phased Array Principle for Beam Focusing

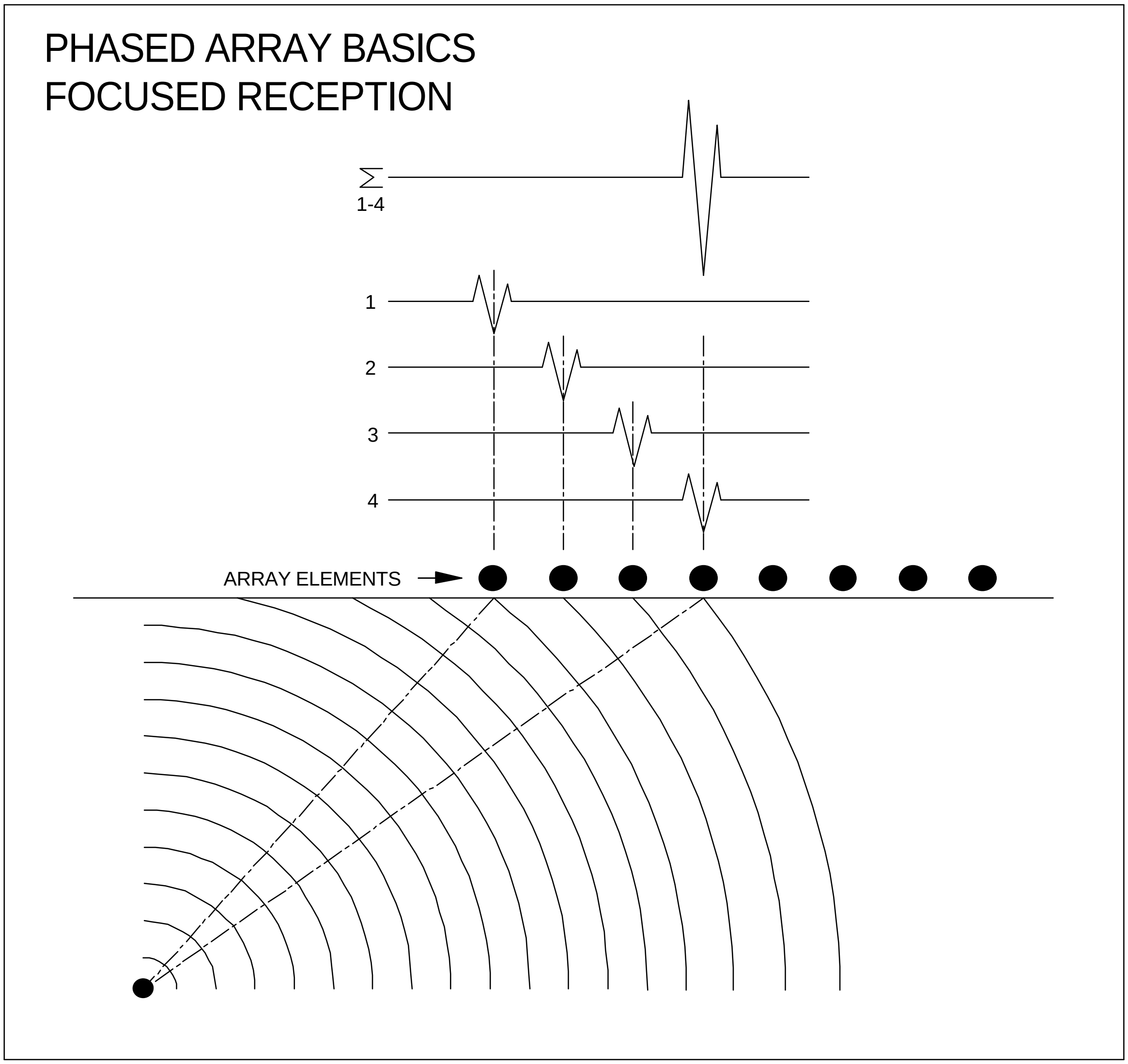


Figure 3-7 Principle of Phased Array Reception

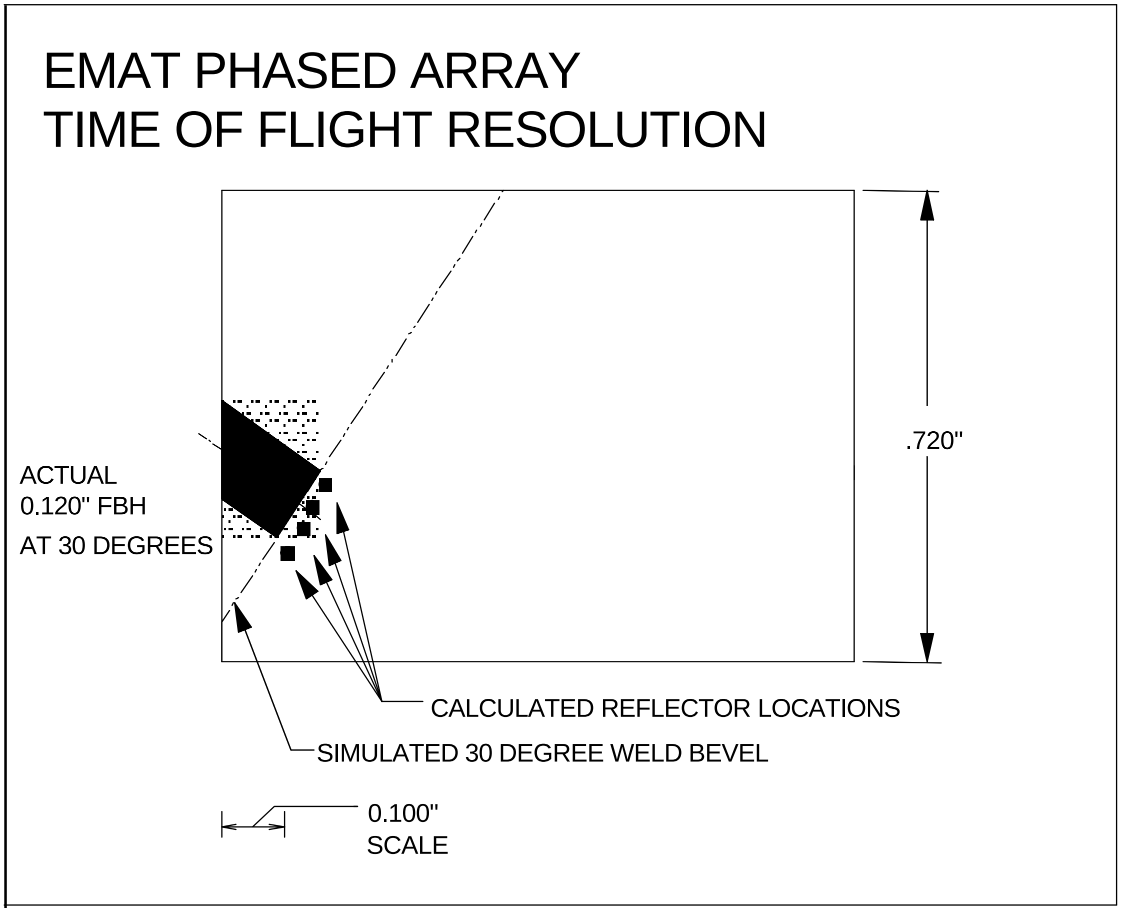


Figure 3-8 Response to 0.120" Dia. FBH Showing Achievable TOF Accuracy

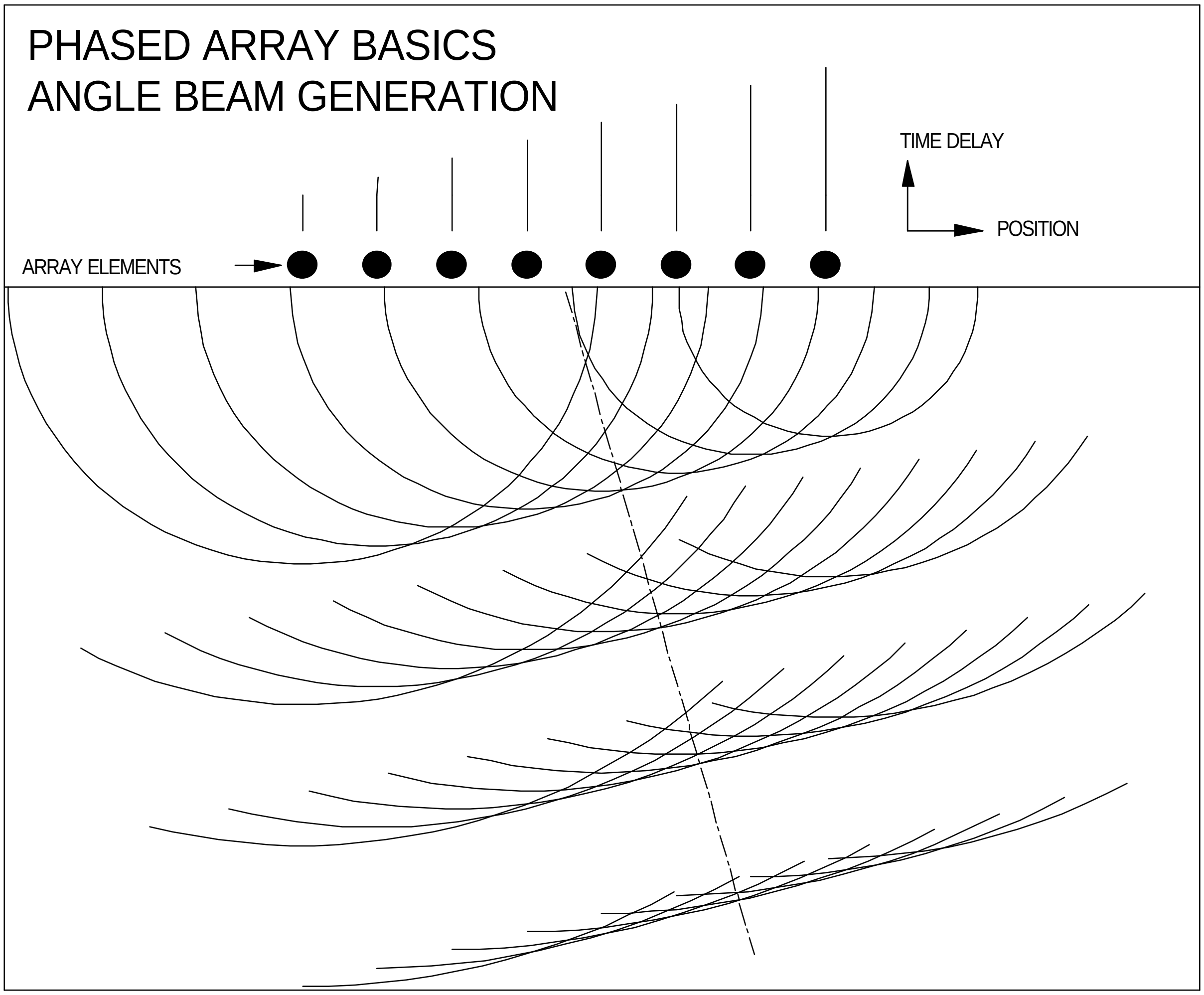


Figure 3-9 Phased Array Principle for Beam Steering

3.3.3.3 Potential Applications in the Shipbuilding Industry

The proven advantages of EMATs, coupled with the enhancing capabilities derived from their phased array operation, together provide unique capabilities for ultrasonic testing that, until recently, have not been available. It is envisioned that these enhanced capabilities will provide significantly greater performance in applications requiring flaw sizing and characterization, and in applications where materials characterization is needed. The shipbuilding industry, in which there are abundance of weldments, piping, and pressure vessels of varying complexities, is an industry that could benefit from the advantages of phased array EMAT NDE. The phased array technology can provide a complete inspection of structure type as well as piping welds. A single scan of the multi-element sensor could perform a surface inspection, eliminating hazardous materials and environmental concerns associated with MT/PT, as well as a volumetric test of the entire weld volume, eradicating the need for radiographic sources and/or linear accelerators. It is estimated that considerable time and expense can be saved with the elimination of environmental and radiographic licensing issues. SH shear wave generation, steering capability from 0-90 degrees, non-mechanical couplant scanning, high focussing, high temperature operation, and superb time resolution all combine to offer an NDE technique highly applicable to the needs of shipyards for materials and flaw characterization. Such a configuration enables very accurate measurement of velocity and attenuation, which have traditionally been good indicators of material degradation. The highly accurate time-of-flight measurements enable flaw sizing and characterization (see Figure 8). Software configurable beam steering further enables the scanning of complex components such as piping welds with minimal probe maneuvering.

3.3.3.4 Results of Phased Array System Evaluation

The initial phased array investigations involved the use of frequency scanned SH waves rather than an actual multi-element phased array sensor. It is possible that the frequency scanned approach could be implemented for volumetric weld inspection at a substantially lower cost than phased array but at the expense of inspection speed. In order to cover the weld volume in the NSWC plates, a beam angle sweep of 11 was used, requiring a frequency change of <25%. Both frequency scanned SH waves and multi-element phased array eliminate the raster motion required in typical ultrasonic volumetric weld inspection. As depicted earlier in Figure 3, the phased array results were simulated by the use of a SH wave C-Scan (pulsed magnet/unfocused 1.2MHz SH sensor @ 60^0 (parallel field)), and there was good agreement with UT/RT results shown on the NAVSEA flaw maps.

Next, testing of the NSWC plates with an actual phased array system was conducted. This was accomplished using hardware and software developed for J Ray McDermott (JRM) for piping girth weld inspection in the offshore pipeline industry. Radiography has, for many years, been the standard NDE method of choice for insuring pipeline weld integrity. Considerable progress has been made in the last decade in developing UT as an acceptable replacement for radiography. UT is now used extensively in automated offshore systems, and results can be superior to radiography, e.g., UT can be more sensitive than RT to LOF in root and hot pass flaws. Noting the potential advantages of EMAT for automated girth weld inspection, JRM funded MTI to develop a prototype system, which electronically scans the cross section of the weld, focussing on the specific areas of interest. The flexibility of electronically controlled scanning of the weld allows the EMAT system to be easily configured for different pipe and weld geometries. Conventional multi-channel UT systems require physically changing the transducers and transducer orientations.

Figure 10 gives the overall system design of the phased array weld inspection system and should be referred to for the following system description. A commercially available phased array hardware component (a) is programmed to provide trigger pulses to a rack of 32 separate EMAT element pulsers (b). Based on pre-programmed trigger excitation, selected pulsers are fired sequentially to provide corresponding pulses to a subset of the 32 individual EMAT coil elements. Selected elements and firing times are based on desired acoustic wave characteristics such as beam angle, focal point, and focal point size, and these parameters are driven by the selected area of the cross section of the weld to which inspection is intended. The transmitting EMAT coil (c) is thus sequentially excited in a manner to generate separate acoustic waves to inspect selected regions of the weld. Reflected acoustic waves from discontinuities are in turn detected with a mirrored EMAT coil counterpart (d). Resulting individual element responses, following amplification, are returned to the phased array hardware to be reconstructed into a typical RF UT signal (basically the reverse of the programmed element excitation for transmission). The resulting RF signal is then processed and displayed to system operators for visual indications of flaws. The above process is completed for both sides of the weld simultaneously. To maintain system compactness, the 32 element pulsers are alternately applied "upstream" and then "downstream" via relay circuits (e) to allow sharing of the bulk of the electronics. Figures 11 and 12 show the cabinet mounted driver electronics, magnet pulsers, and phased array hardware. The remote electronics (preamplifiers and impedance matching) and pulsed magnet EMAT sensor are shown in Figure 13.

The results of the testing with the phased array system are shown in Figures 14 and 15. The NAVSEA flaw maps for plate A18 can be seen in Figures 16a and 16b. Figure 14 is a B-Scan or cross-sectional representation of the response of the phased array system to a LOF defect located 0.9" below the top surface. The illustration, a "slice" through the plate cross section at a specific location, clearly shows that the flaw lies on the fusion line of the weld. This is consistent with a LOF type flaw and is distinguishable from porosity which tends to be randomly located throughout the weld volume. The phased array system response to porosity is pictured in the B-Scan of Figure 15. Again, the "slice" through plate 18A at this specific location reveals a flaw located 1" below the top surface, corresponding well to the NAVSEA flaw map. In order to visualize the flaw with respect to the weld, a cross sectional view of the weld has been drawn by hand on both B-Scans. This could be done automatically in software in subsequent versions of EMAT phased array systems.

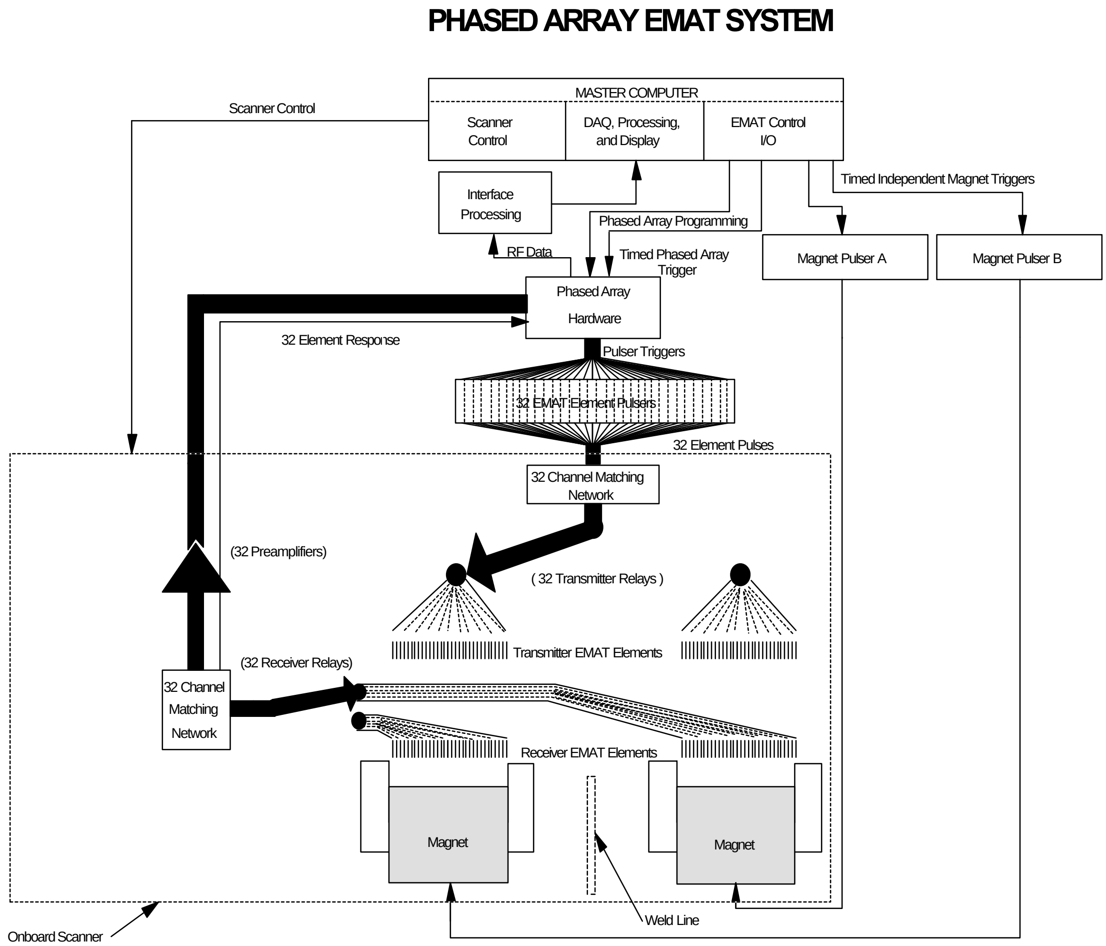


Figure 3-10 32 Channel Phased Array System Configuration for Volumetric Weld Inspection

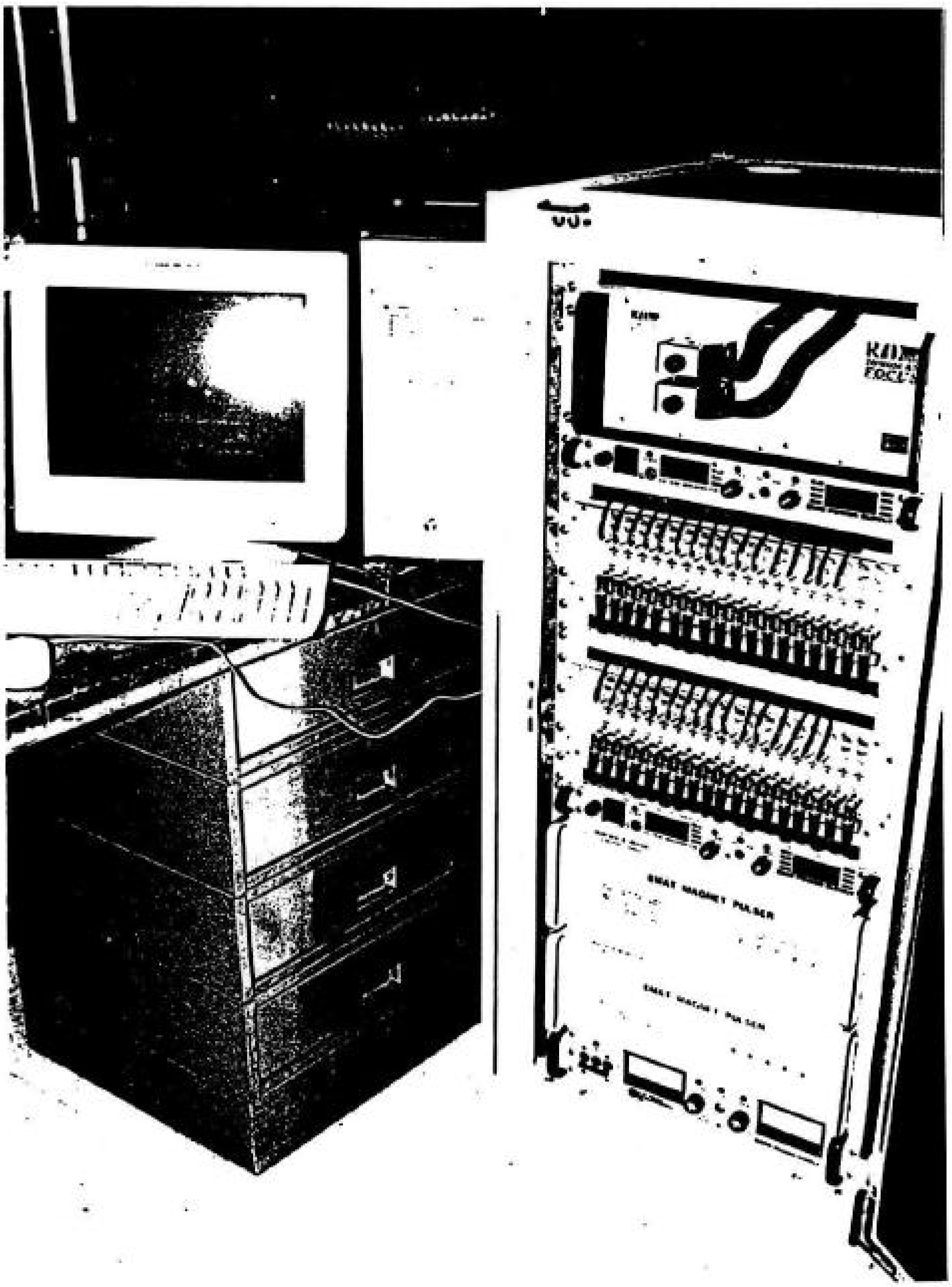


Figure 3-11 EMAT Driver Electronics for Phased Array Weld Inspection System

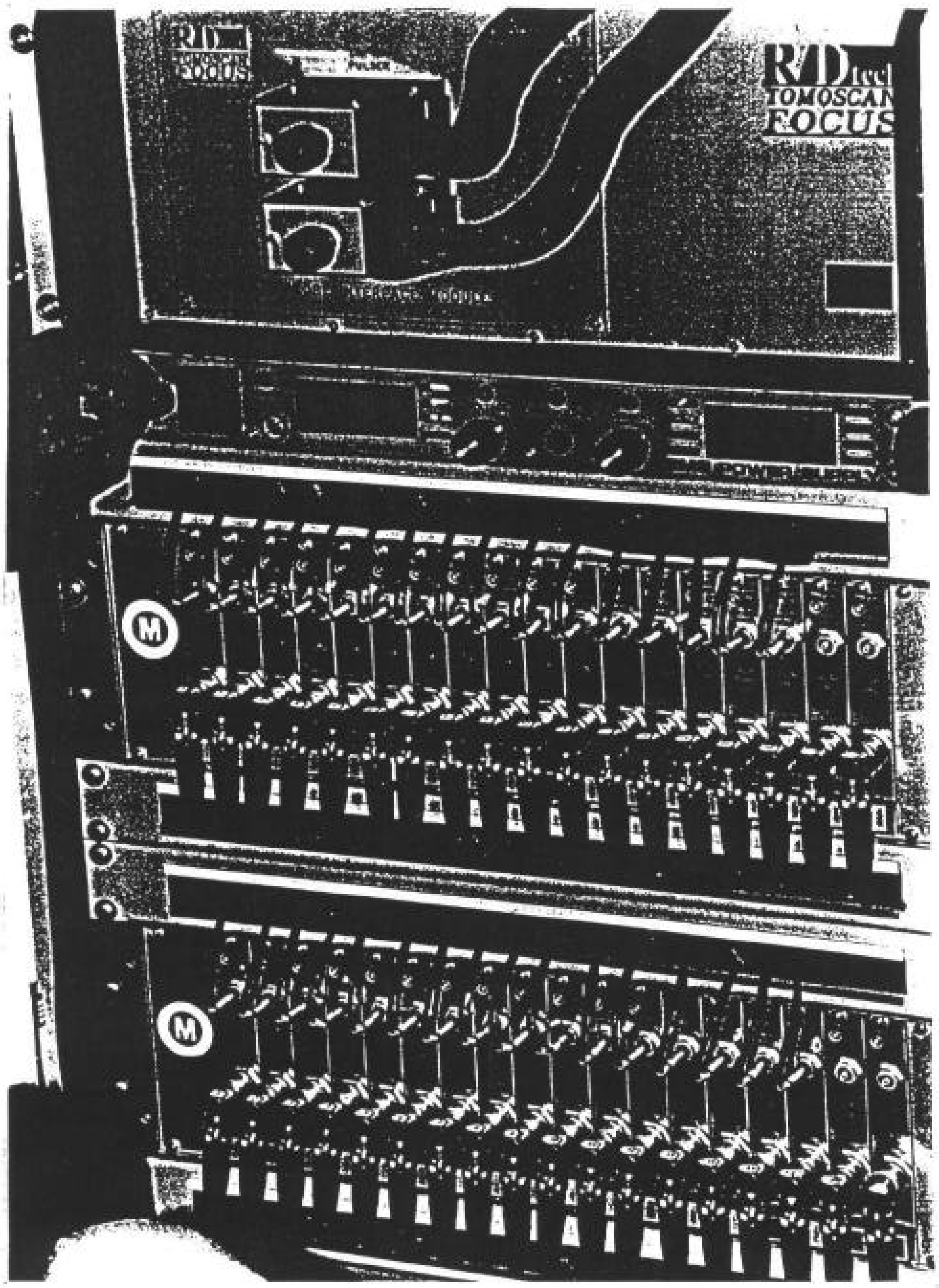


Figure 3-12 Closeup View of 32-Channel EMAT Pulser and Phased Array Hardware

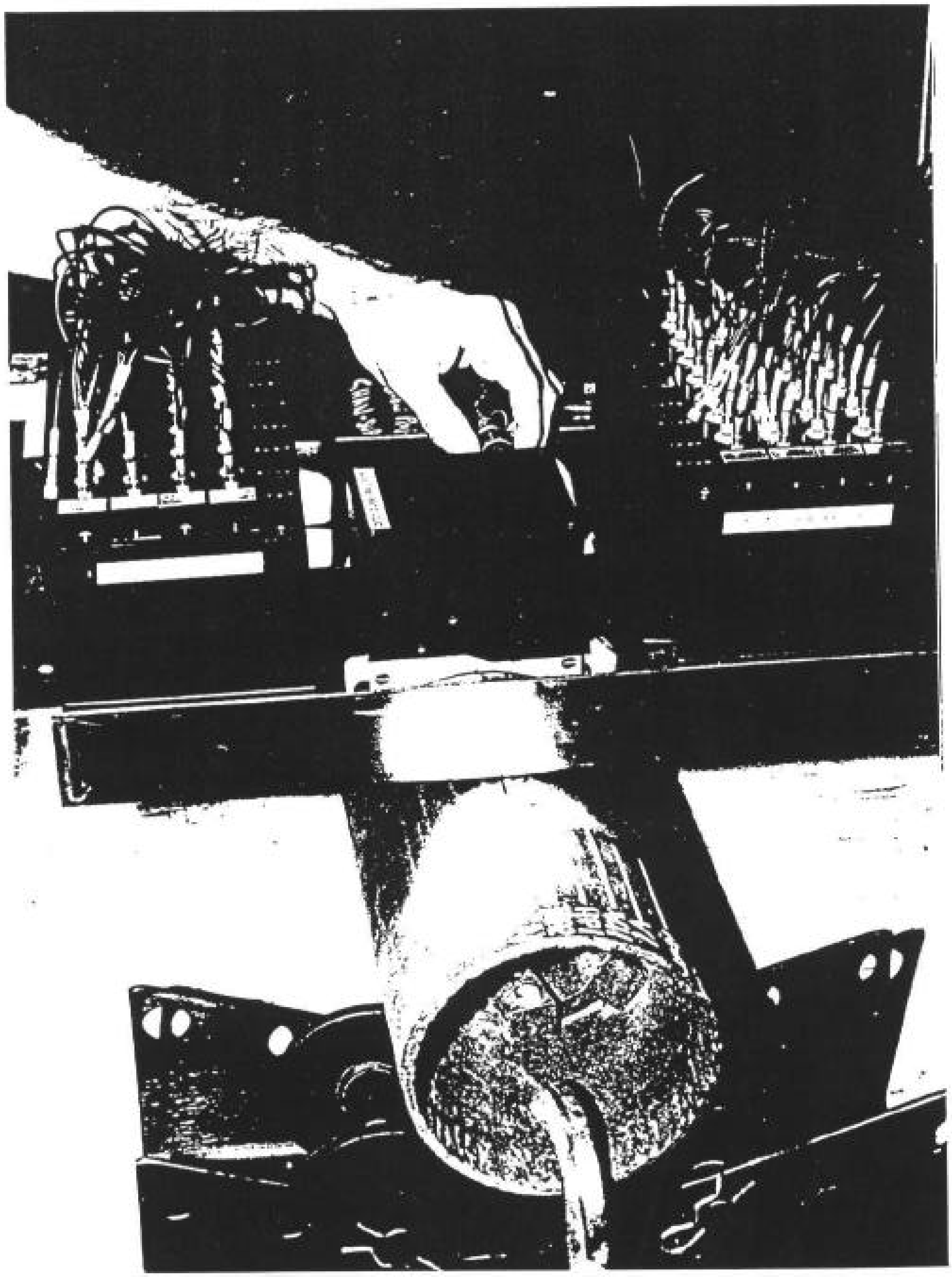


Figure 3-13 Pulsed Magnet EMAT Sensor and Remote Electronics for Weld Inspection

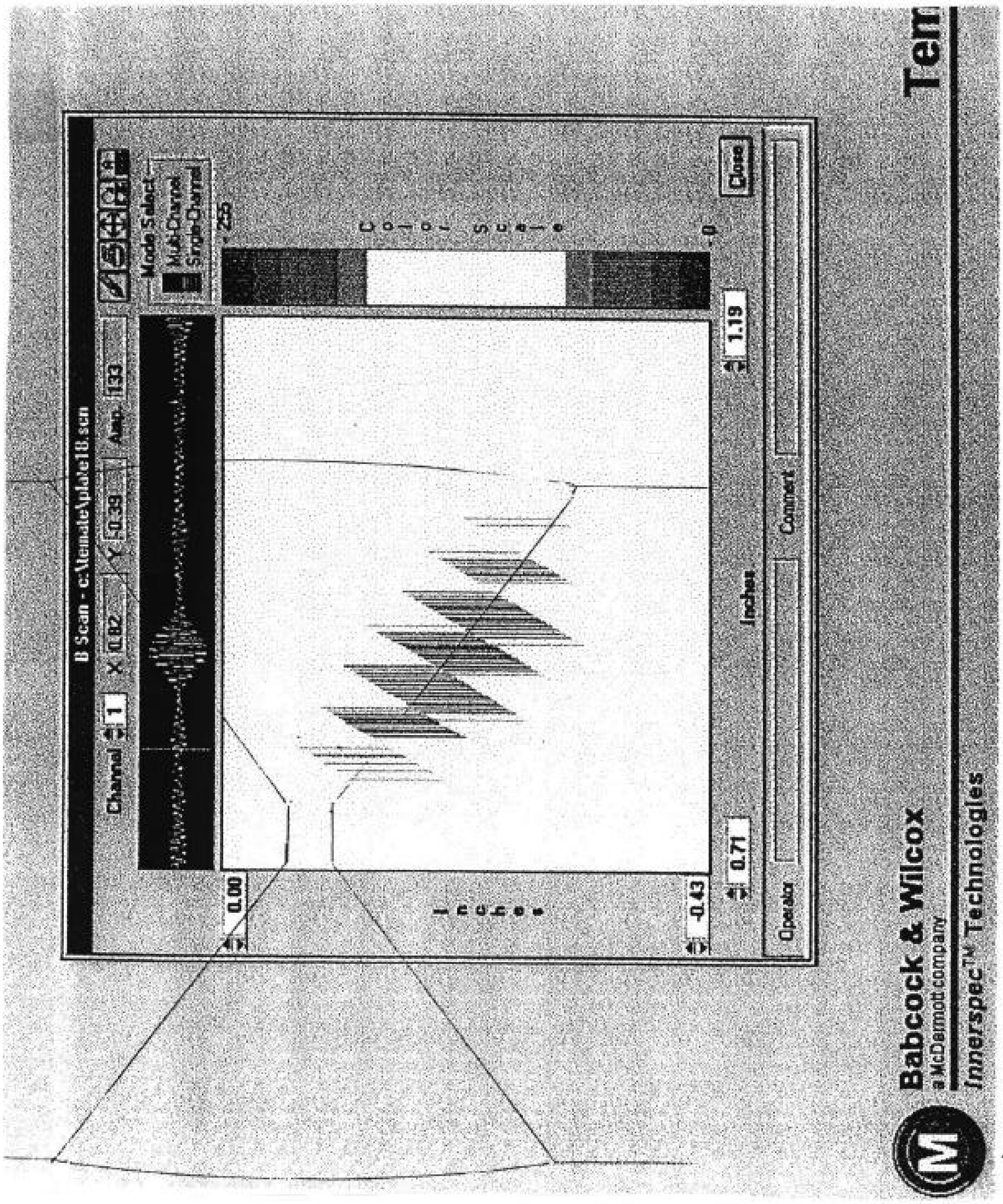


Figure 3-14 B-Scan Results of Phased Array EMAT Testing of NSWC Plate A18 (Cross Sectional View of Weld Showing LOF Defect on Fusion Line)

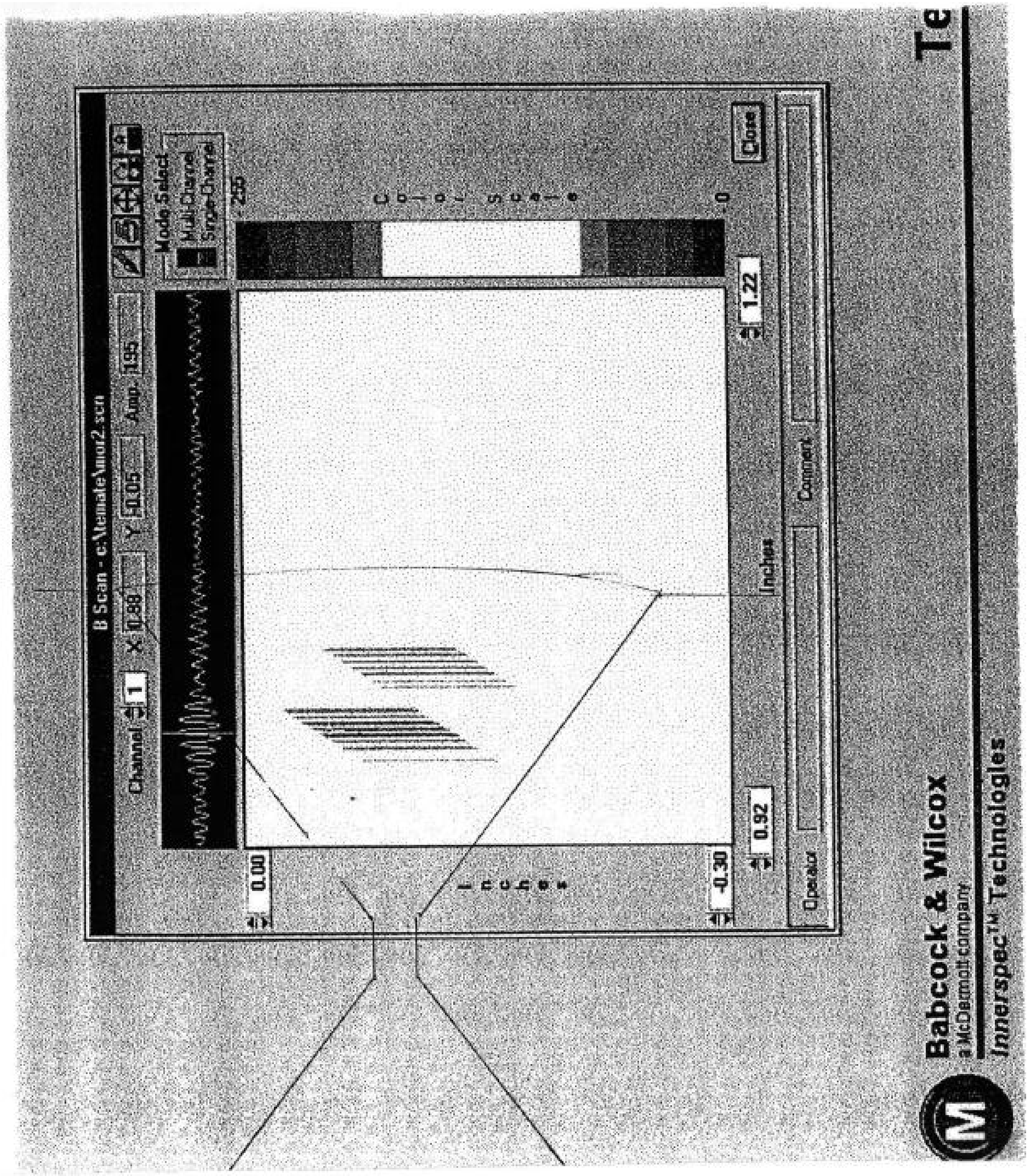


Figure 3-15 B-Scan Results of EMAT Phased Array Testing of NSWC Plate A18 (Cross Sectional View of Weld Showing Porosity in Weld Volume)

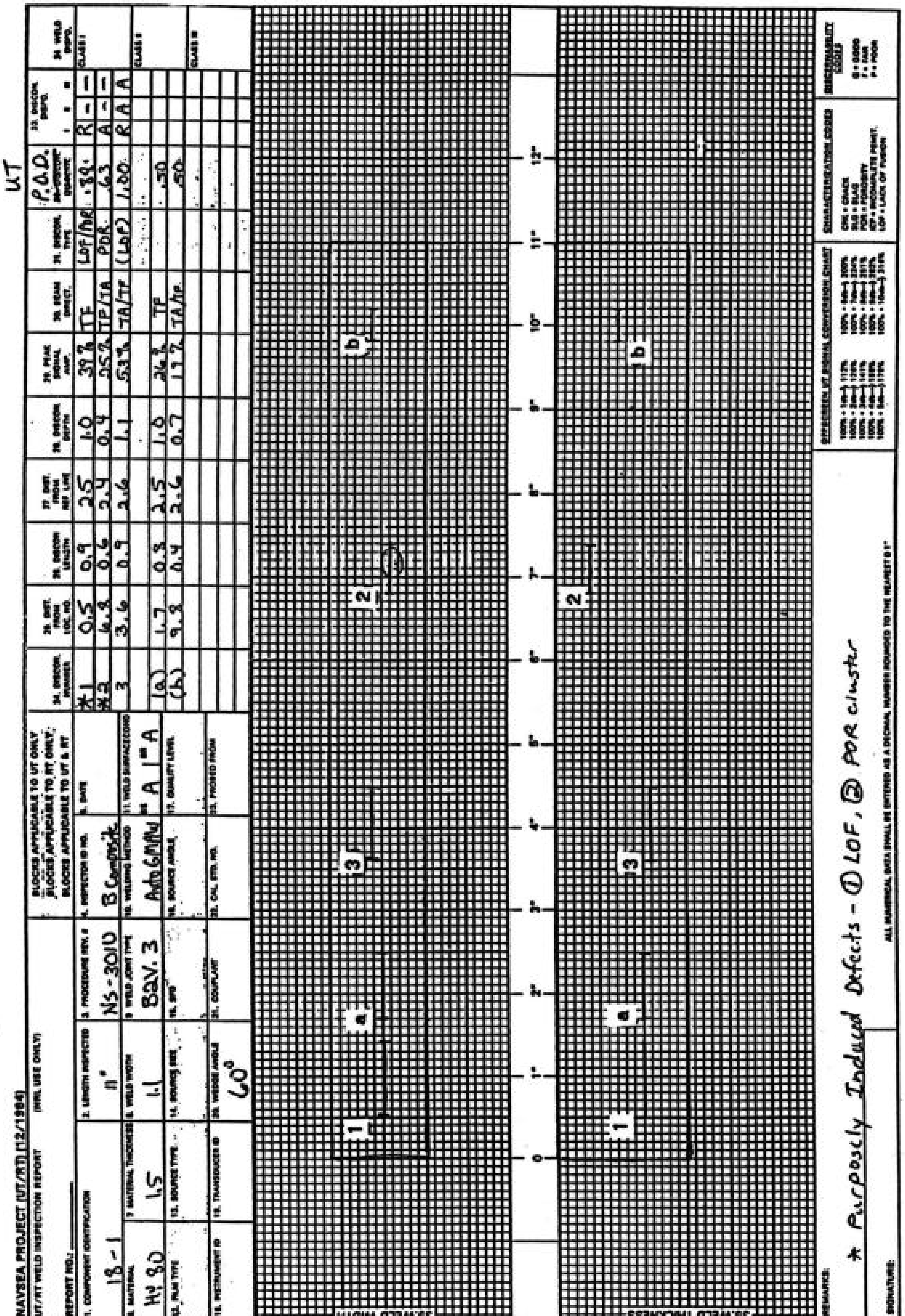


Figure 3-16a Flaw Map Showing NAVSEA UT/RT Results for NSWC Plate A18-1

Figure 3-16a Flaw Map Showing NAVSEA UT/RT Results for NSWC Plate A18-1

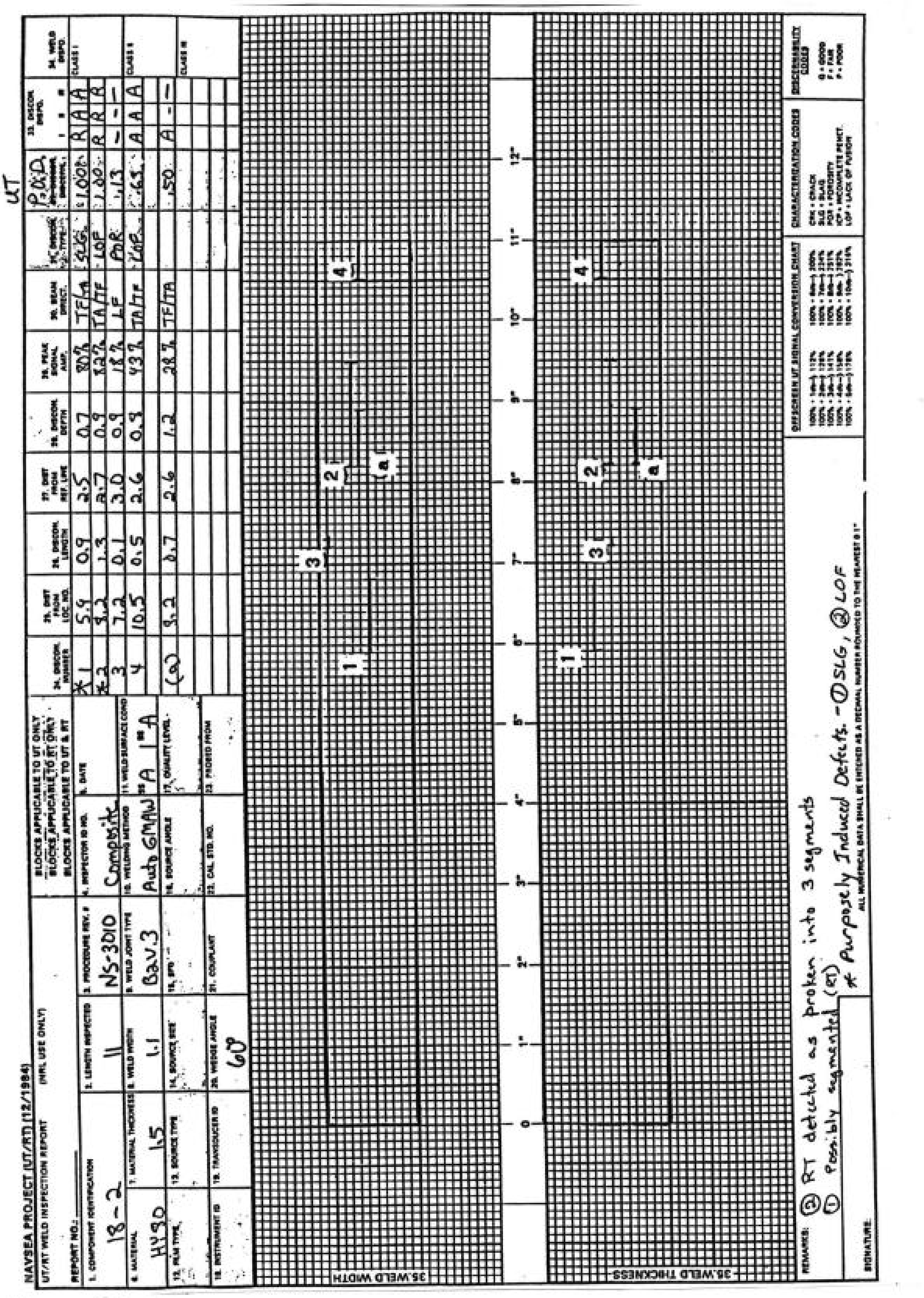


Figure 16b Flaw Map Showing NAVSEA UT/RT Results for NSWC Plate A18-2

3.4 CONCLUSIONS

- It should be noted that all EMAT evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

- In an earlier project funded by KAPL/EB, the results of shipyard evaluations of a diffraction-based volumetric test were indefinite because the test was found to be too sensitive to slag inclusions/scattered porosity. Since the diffraction test was seen to have difficulty in discriminating between insignificant porosity and the ends of a significant flaw, e.g., LOF, the decision was made to discontinue further development of the diffraction approach.

- The over sensitivity to scattered porosity was found to be caused by the use of a focused sensor.

- The initial non diffraction-based volumetric evaluations were conducted using a permanent magnet/unfocused 2MHz SV sensor, resulting in insufficient S/N for LOF. However, the unfocused sensor did minimize sensitivity to insignificant porosity.

- Subsequent 2MHz SV work relied on the use of a pulsed magnet and unfocused sensor with the following results:

  - Normal incidence - minimal response to porosity
  - Good system portability
  - Good S/N for LOF (10:1)
  - Fixed 32 beam angle - too sensitive to weld root/crown
  - Poor correlation with NAVSEA UT/RT results on NSWC test plates

- The magnetic properties of the high strength steels used in ship construction were found to be conducive to magnetostrictive generation of ultrasound. Magnetostriction enables the use of SH waves to perform the volumetric inspection of welds. The use of a pulsed magnet and unfocused 1.2MHz SH sensor @ 60^0 beam angle (parallel field) provided the following results:

  - Normal incidence - minimal response to porosity
  - Good system portability
  - Good S/N for LOF (>10:1)
  - Minimal response to scattered porosity & weld root/crown
  - Good correlation with NAVSEA UT/RT results on NSWC test plates

- Frequency scanned SH waves can improve volumetric weld inspection.

  - Beam can be swept (0-90) by small changes in test frequency
  - Covers complete weld volume, eliminating raster probe motion
  - Good correlation with NAVSEA UT/RT results on NSWC test plates
  - Less expensive than phased array, but much slower

- Phased array technology permits simultaneous surface/volumetric inspection of welds.

- Phased array technology provides not only the ability to detect flaws, but also allows complete weld characterization, i.e., it provides the capability to distinguish between significant flaws (LOF) and insignificant defects (scattered porosity).

- The incorporation of phased array technology offers enhanced performance capabilities for EMATs for weld inspection applications. Advantages include:

  - Excellent time-of-flight resolution for accurate velocity measurements
  - Removal of couplant influences for more accurate measurements (e.g., attenuation)
  - Generation of broadband signals more conducive to frequency analysis
  - High degree of signal reproducibility (derived from lack of couplant variations and reproducible transducer design and control) to enable application of feature extraction and pattern recognition algorithms or neural networks for classification of degradation
  - Enhanced scanning capability with limited probe movement requirements for applications involving complex geometries
  - Software control of focal spot size, depth, and angle, allowing for rapid scanning of many configurations
  - Ability to easily utilize any of the wave modes, including the SH wave mode, which is difficult to apply in a scanning mode with conventional UT

3.5 RECOMMENDATIONS

- Investigations concerning volumetric inspection of structure type shipyard welds with EMAT are considered to be complete. Discussions with NAVSEA in November, 1997 indicate that individual yards will be expected to make their cases for use of the technique for replacement of conventional volumetric inspection methods, e.g., UT and RT. In those cases where NAVSEA or applicable manufacturing code does not stipulate NDE requirements or prohibit the use of EMAT for volumetric inspection of welds, it is recommended that EMAT be pursued. There are commercial manufacturers of EMAT probes/electronics which can provide production systems, including spare parts, warranties, and service. MTI is prepared to assist the yards in implementation of the EMAT technology for volumetric inspection.

- Complete current phase of SP-7 project, focusing on piping welds.

- Get additional samples of welded pipe from EB and/or Puget.

- Complete internal MTI programs (phased array EMAT system evaluations on JRay McDermott (JRM) offshore lay barge project) to leverage volumetric weld inspection technology for the SP-7 panel.

- Maintain data base on JRM project (EMAT results vs. RT) and attempt to get access to Shaw Pipeline Services (vendor of current UT system for piping girth weld inspection system) data base (UT vs. RT).

4.0 REFINEMENT OF SURFACE EXAMINATION METHODS

DEVELOPMENT OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS) FOR SURFACE/VOLUMETRIC INSPECTION OF WELDS

- FINAL SUMMARY REPORT -

REFINEMENT OF SURFACE EXAMINATION METHODS

PREPARED BY

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January 17, 2000

PREPARED FOR

HALTER MARINE GROUP, INC.
GULFPORT, MS
AND
NAVAL SURFACE WARFARE CENTER

HMGI PURCHASE ORDER NO. 2228
PROJECT NO. 7-96-1
MTI CONTRACT NO. CRD - 1355

4.1 SUMMARY

This report summarizes the results of a specific task, *Refinement of Surface Examination Methods*, in National Shipbuilding Research Program (NSRP) Project 7-96-1, "ElectroMagnetic Acoustic Transducers (EMATs) for Surface/Volumetric Inspection of Welds". Project 7-96-1 is a continuation of two earlier projects concerning shipyard application of EMATs for surface and volumetric weld inspection. An initial feasibility study (7-91-3) completed for the SP-7 Welding Panel in June, 1994 demonstrated laboratory feasibility for the use of EMAT generated surface waves to replace magnetic particle (MT) and/or liquid penetrant (PT) for surface inspection of welds. A subsequent project funded by Knolls Atomic Power Lab (KAPL) through General Dynamics - Electric Boat (EB) extended the EMAT technology by evaluating shear wave sensors for volumetric weld examination and included system evaluation in the shipyard, comparing the results to conventional inspection methods (MT, PT, ultrasonics (UT), and radiography (RT)). The results of the shipyard evaluation of the surface wave test were positive, while the outcome of the shear wave investigation for volumetric weld inspection was somewhat inconclusive. These conclusions led to the proposing of additional EMAT evaluations to the SP-7 Welding Panel, resulting in Project 7-96-1, a two year program divided into two phases. This report describes the results of one of two tasks in Phase 1.

Evaluation of the surface wave test is now complete, and the test should be considered ready for implementation by the various SP-7 member shipyards. McDermott Technology, Inc. can assist the shipyards in obtaining EMAT electronics, sensors and support, but the individual yards will need to determine their own requirements for system deployment. The diffraction-based test is capable of high speed scanning and detection of surface-breaking as well as subsurface flaws in structure type welds. The attenuation based test is suitable for even higher speed inspection and detection of surface-breaking and subsurface flaws in mechanized or automatic welds. In addition, the attenuation technique can be employed for extremely rapid surface inspection of painted base material.

In order to initiate the process of Navy approval for the EMAT inspection method, a meeting was held In Washington, D.C. in November, 1997 with two Navy shipyards (EB & Newport News Shipbuilding) and NAVSEA present. The purpose of the meeting was to determine the requirements for implementation of the surface wave test in Navy yards. NAVSEA indicated that it will be the responsibility of the shipyards to make their intentions known to NAVSEA and then to build their case for approval of the EMAT method for surface inspection of welds.

4.2 INTRODUCTION / BACKGROUND

A comprehensive overall introduction and background for the project is given at the beginning of this final report.

4.3 REFINEMENT OF SURFACE EXAMINATION METHODS

There were two different EMAT methods used in the laboratory evaluations for surface inspection of welds. One technique was based on diffraction and uses a single sensor operated in the pulse-echo mode, while the other method, based on attenuation, employs two pairs of transmit-receive coils arranged in an X-pattern. In both cases, a remote electronics module mounted on or adjacent to the probe head contains low noise preamplifiers and transmitter impedance matching networks, allowing the use of long cables between the probe head and the EMAT electronics unit.

4.3.1 Zig-Zag (Attenuation Technique)

This technique is based on the attenuation of pitch-catch surface waves by a surface-breaking flaw. The unique aspect of this technique is the fact that this technique detects all flaw orientations with one linear scan. The basic principles of the technique are shown in Figure 1. Two pitch-catch sensors pairs are arranged in a diagonal pattern. A flaw between one pitch-catch pair of sensors will partially or totally block the ultrasonic beam and cause a loss of signal. This particular pair of sensors is not sensitive to flaws aligned parallel to the beam. However, the other pair of pitch-catch sensors, oriented in an orthogonal direction to the first pair, will be positioned for maximum sensitivity. With this combination, all flaw orientations can be detected by one linear scan of the composite sensor. The "X" pattern for the EMAT coils shown in Figure 1 allows the maximum area to be covered by a linear scan of the transducer over the test piece. After one linear scan of the transducer over the component, an area equal to the length of the scan times the perpendicular distance between the EMAT coils will have been inspected for all orientations of surface breaking flaws. The positioning of the sensors allows inspections close to the edges and other areas that are difficult to inspect. The separation of the array of sensors can be changed to vary the width of the inspection band from very short distances to spans covering one to two feet.

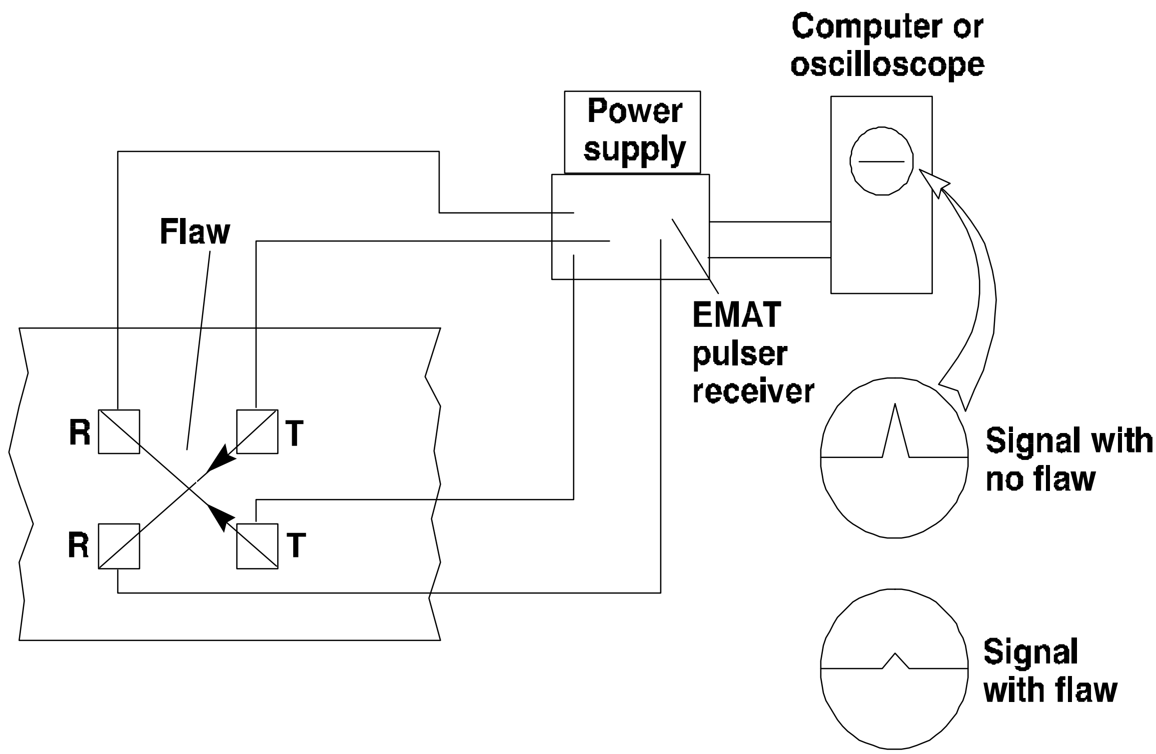


Figure 4-1 Attenuation technique for surface inspection of welds (Zig-Zag)

The Zig-Zag sensor uses four 2 MHz meander coil (unfocused) surface wave EMATs. The magnets used were 1/2" x 1/4" rectangular Neodymium Iron Boron (NdFeB) permanent magnets. The sensors are positioned in a fixture that straddles the weld and is translated along the crown of the weld. The fixture is shown on a weld in Figure 2. Figure 3 illustrates the bottom of the fixture showing the individual sensor coils. Proper selection of spacing between coils allows two coil pairs to be connected in series and driven with a single channel of EMAT electronics.

The frequency can be chosen to correspond to the desired depth of penetration, providing for some detection capabilities for sub-surface defects. For Rayleigh (surface) waves, the depth of penetration is approximately one wavelength. Therefore, a 2 MHz EMAT would have a depth of penetration depth of 0.060", and a 1 MHz EMAT would have a depth of penetration of 0.120", etc.

The test methodology employed with the attenuation technique allows for extremely high speed surface inspection of either base metal or automatic/mechanized welds. Since the test is based on attenuation or "loss of signal" the technique is not suitable for rough, manual welds or complex geometries. It should be noted that the test can operate on painted surfaces (applicable to paint thicknesses up to 15 mils thick).

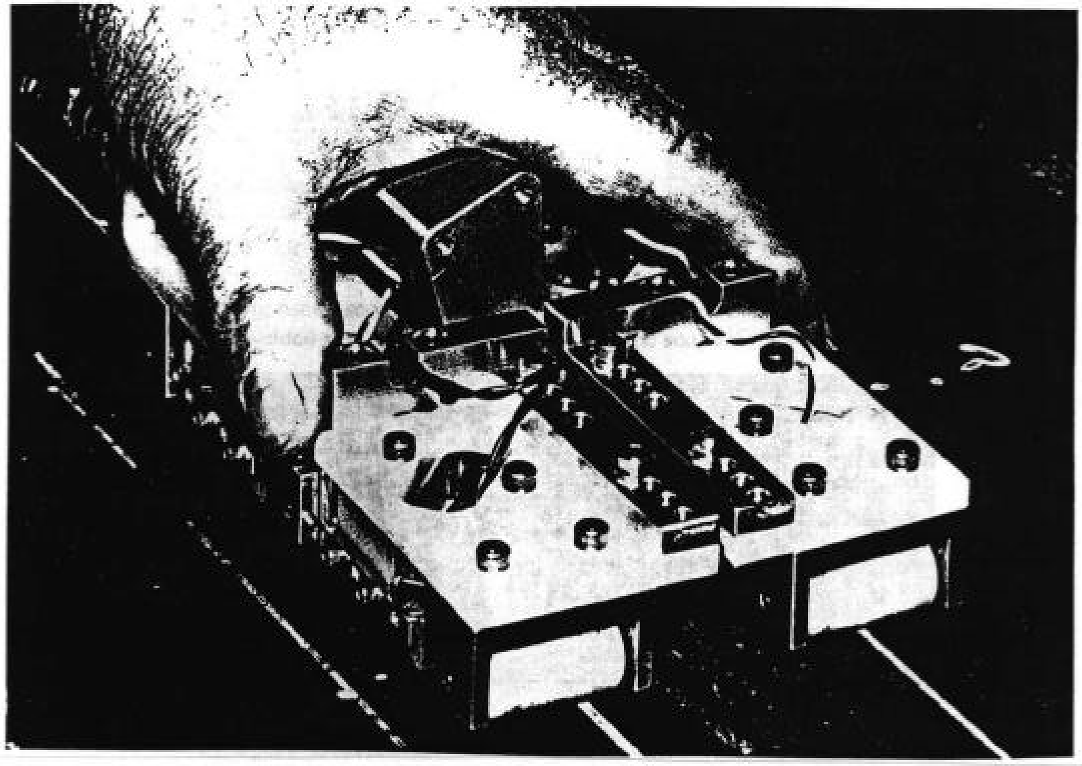


Figure 4-2 Attenuation EMAT Sensor for Surface Exam of Welds/Base (Zig-Zag)

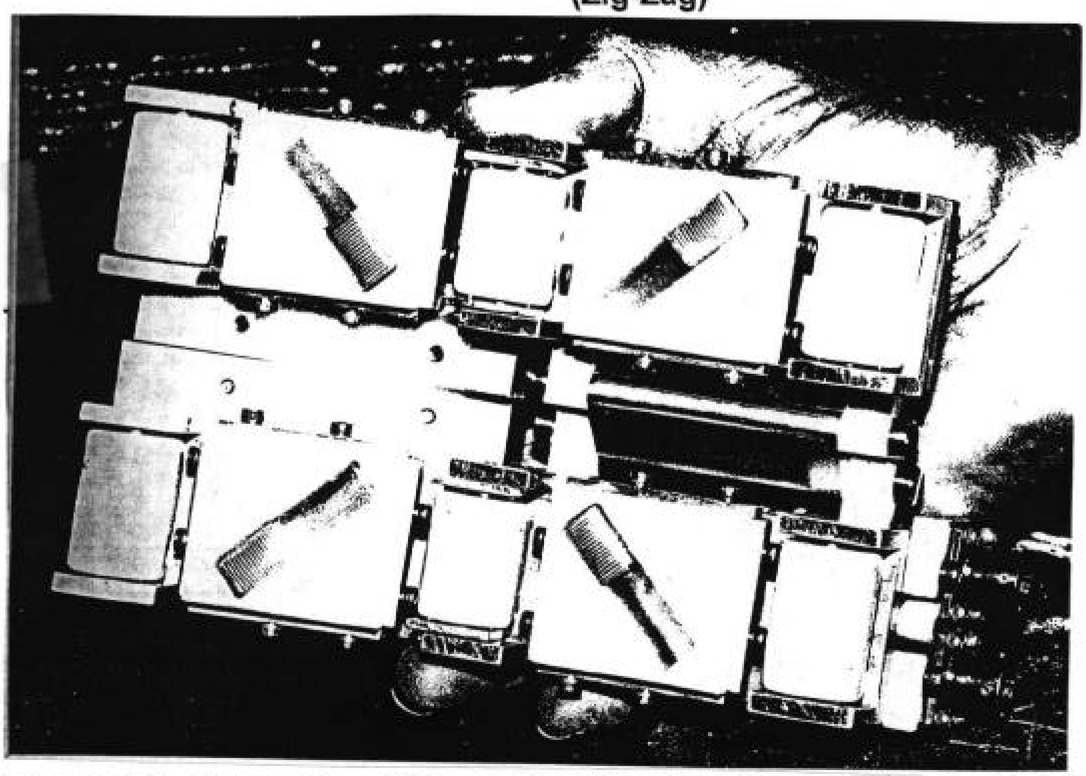


Figure 4-3 Underside of Attenuation (Zig Zag) Sensor Showing RF Coils

The following oscilloscope printouts show the response of the Zig-Zag sensor to a surface-breaking flaw in a welded steel plate. Figure 4 presents the scope display when no flaw is present, and Figure 5 shows an approximate 6 dB drop in signal amplitude caused by a 0.125" long x 0.062" deep transverse notch in the crown of the weld (FCAW in as-welded condition).

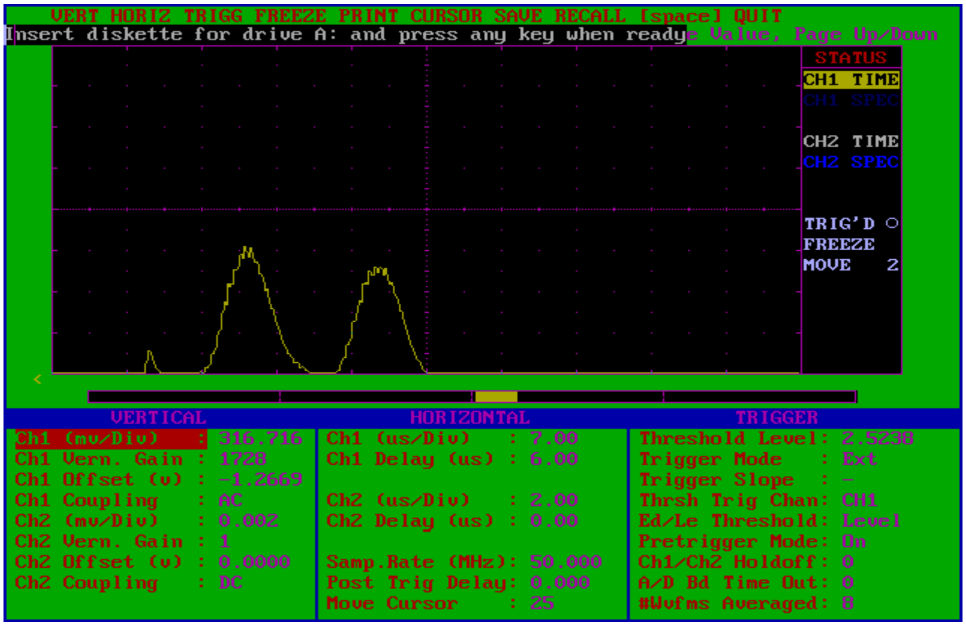


Figure 4-4 Zig-Zag Scope Display When No Flaw is Present

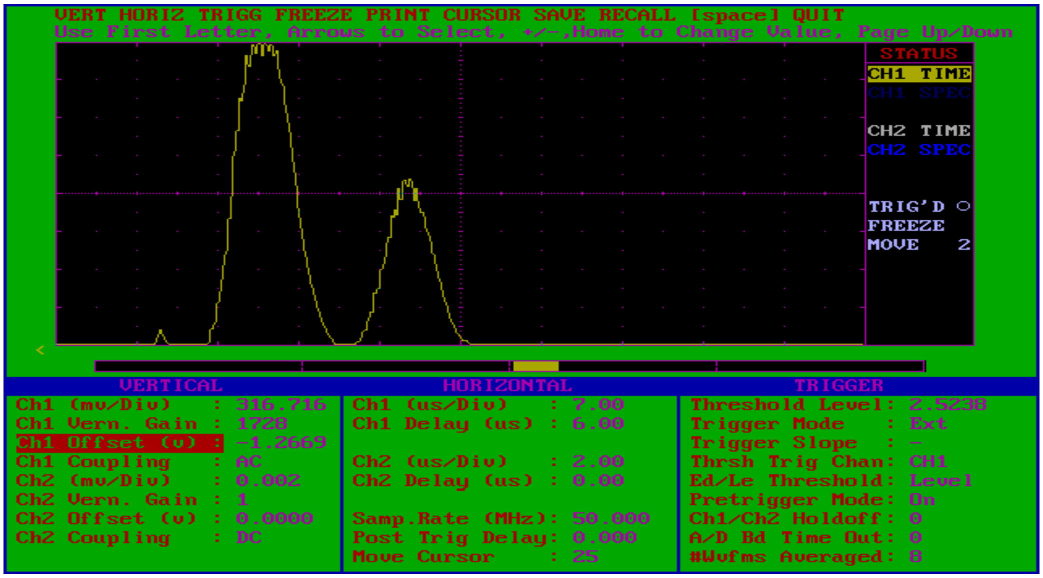


Figure 4-5 Zig-Zag display showing 6 dB drop in signal amplitude caused by a 0.125" long x 0.062" deep transverse notch in the crown of weld (FCAW in as-welded condition)

4.3.2 Diffraction Technique

EMATs are particularly useful for weld examination because no couplant is needed, allowing rapid scanning at either ambient or elevated temperatures. In conducting a surface inspection of a weld with ultrasonics, geometrical reflectors such as the crown and toe produce signals which can interfere with and even obscure the signal from actual flaws. MTI has developed a technique based on diffraction that eliminates the signals reflected from the weld geometry, but clearly shows the flaw indication, greatly simplifying data interpretation. The diffraction technique is used in this project for surface inspection of welds for replacement of MT/PT, and the test is capable of eliminating the crown and toe signals in a single linear weld scan. While the test removes spurious noise and confusing signals attributed to the weld bead, the defect signals are presented clearly, even in the as-welded condition. This technique uses a collinear set of focused EMAT sensors rotated at an angle with respect to the weld center line. The frequency is chosen so that the wavelength is comparable to the flaw dimensions. As a result, the flaw can be detected by diffraction over a wide range of angles, but the toe and crown signals are reflected away as specular reflectors. The diffraction technique is illustrated in Figure 6. The pitch-catch

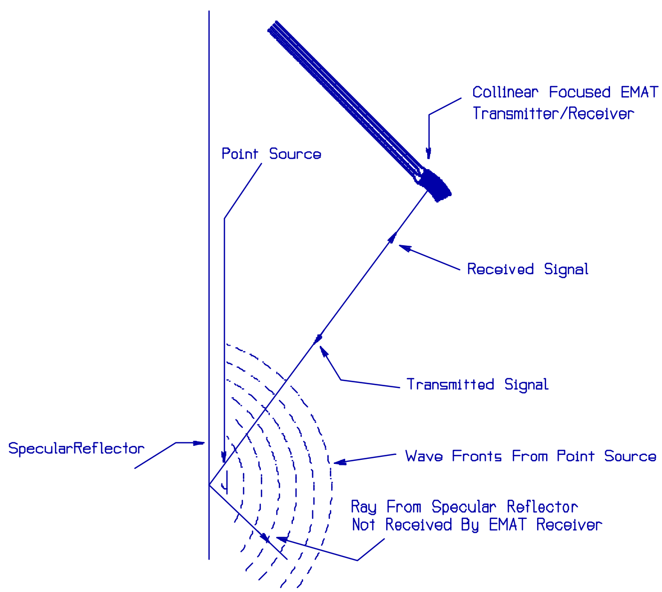


Figure 4-6 Diffraction Technique for Surface Inspection of Welds.

set of focused EMATs is rotated at a suitable angle with respect to the weld centerline. In practice, the angle can be any convenient value (for example 45^{o}), if the wavelength of the sound is sufficiently close to the flaw dimensions such that the flaw acts as a point source and exhibits a wide angular diffraction pattern. This technique has the advantage that the angle can be easily changed. In practice, flaws parallel to the angle of incidence are not detected; therefore, another sensor can be aligned at a right angle on the same probe to provide simultaneous detection of all flaw orientations.

In order to increase the signal to noise ratio for small flaws using the diffraction technique, focused sensors were used for the surface inspection techniques. The surface wave coils are operated in the pitch-catch mode with a focal length of 2.5", resulting in a point or spot focus. A frequency of 1MHz was used. The diffraction angle (angle of the sensor with respect to normal to the weld axis) for the surface wave coil was 32 .

The EMAT coil consists of a flexible printed circuit using a thin layer of copper on a substrate of 0.002" thick Kapton[7]. The initial work was conducted using a protective wear plate of 0.003" thick Ultra High Molecular Weight Polyethylene (UHMW). Although the UHMW has been shown to provide an extremely durable wear face, even in very harsh environments such as a ship fabrication yard, a superior wear face material - Havar[7] (an alloy of Cobalt/Nickel/Chromium) - was identified for use on the production probe. A thickness of 0.002" of Havar[7] was found to provide excellent sensor longevity with minimal loss of signal amplitude. An example of the meander EMAT coil is shown in Figure 7.

The magnetic field, oriented normal to the test surface, was supplied by a 1 inch cube neodymium iron boron (NdFeB) permanent magnet. The EMAT coil is backed by a thin strip (~0.062" thick) of compliant foam to maintain contact between the coil and the uneven surface of the welded plate. A thin strip (~0.001" thick) of copper was placed next to the magnet to prevent sound propagation into the magnet. The UHMW or Havar[7] strip maintains a constant liftoff between coil and test piece, and the foam backing allows the flexible printed circuit EMAT coil to conform to an irregular surface. The EMAT sensor is mounted in a compact fixture that is rolled along the edge of the weld. In fact, the toe of the weld can be used as a sensor scanning guide in many cases. The fixture maintains the diffraction angle with respect to the weld centerline. A photograph of the hand-held fixture positioned on a welded mockup is shown in Figure 8. Figure 9 shows a close-up of the probe underside, showing the focused sensor coil covered with UHMW. Use of the Havar® wear face is depicted in Figure 10. In production use, the sensor head could contain two sensors at right angles to insure detection of all flaw orientations with one linear scan.

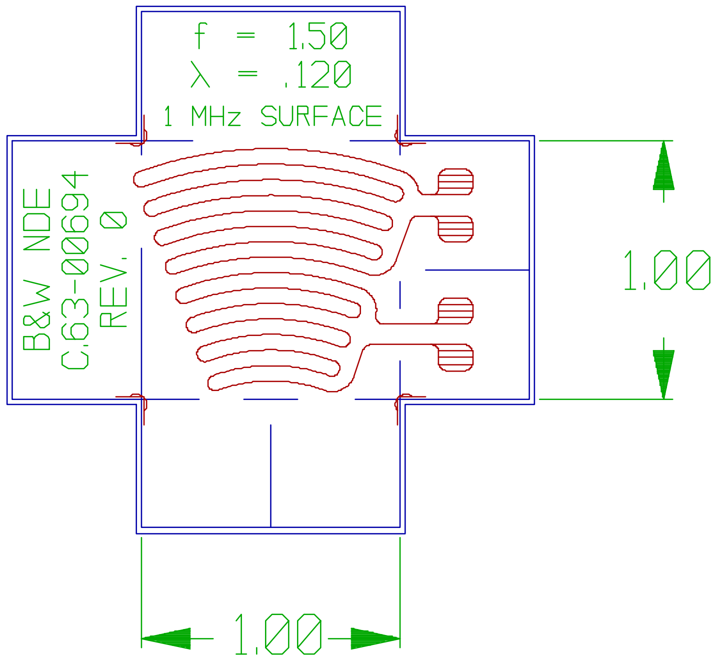


Figure 4-7 Example of EMAT Coil Used in Diffraction Technique (in inches)

In order to determine the capabilities of the diffraction test on complex geometries, a welded mockup containing corners, tees, and butt welds was provided by EB. A drawing showing the various welding techniques used to fabricate the mockup is shown in Figure 11. A photograph of the mockup undergoing lab evaluation is shown in Figure 12. In order to determine flaw detection capabilities in the assorted weld geometries, a variety of flaws approximately 0.125"L X 0.060"D were placed in the welds in different locations/orientations. Figure 13 presents the mockup flaw positions and Table 1 gives specific information regarding flaw type, depth and location.

The results of the testing of the EB mockup with the diffraction technique demonstrated that all flaws could be detected with good signal-to-noise ratio (S/N) except in the corners. The best results were seen when testing the butt welds with S/N exceeding 20:1. Good results were also obtained with the manually welded fillets. Even though these welds were "rough" compared to the butt weld, S/N of > 15:1 were seen. Figures 14-20 show the results of testing the EB mockup using the diffraction method for surface inspection of welds. These figures are A-Scan presentations from an oscilloscope showing the response of the surface wave to the different flaws in the mockup (labeled "indication" in the figures).

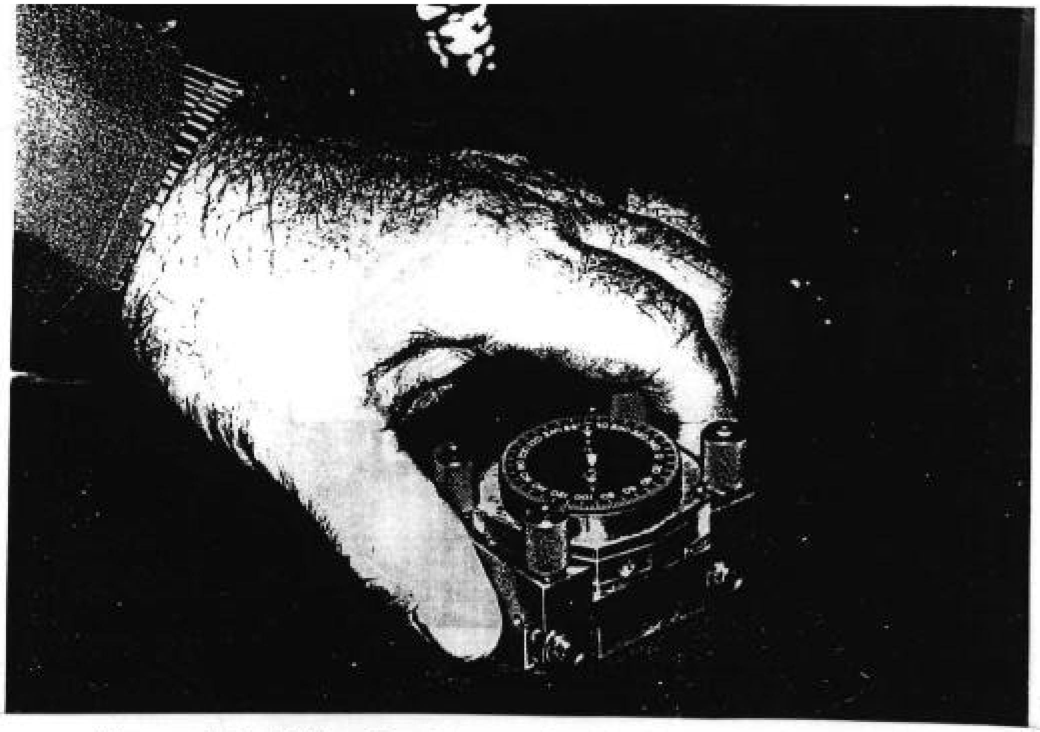


Figure 4-8 Diffraction Sensor for Surface Testing of Welds

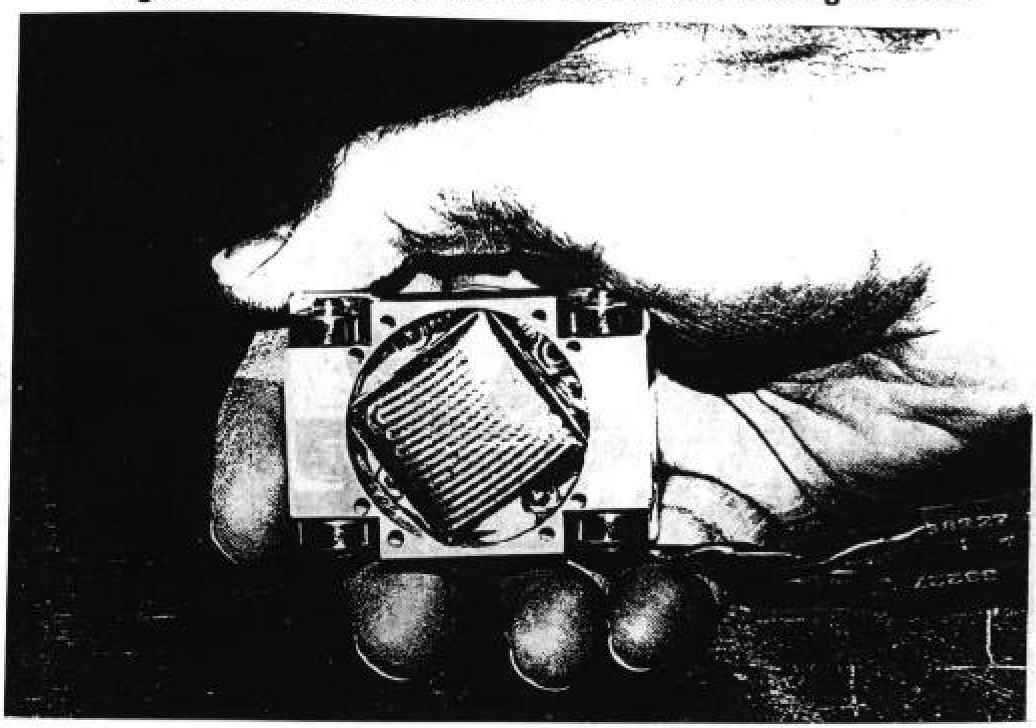
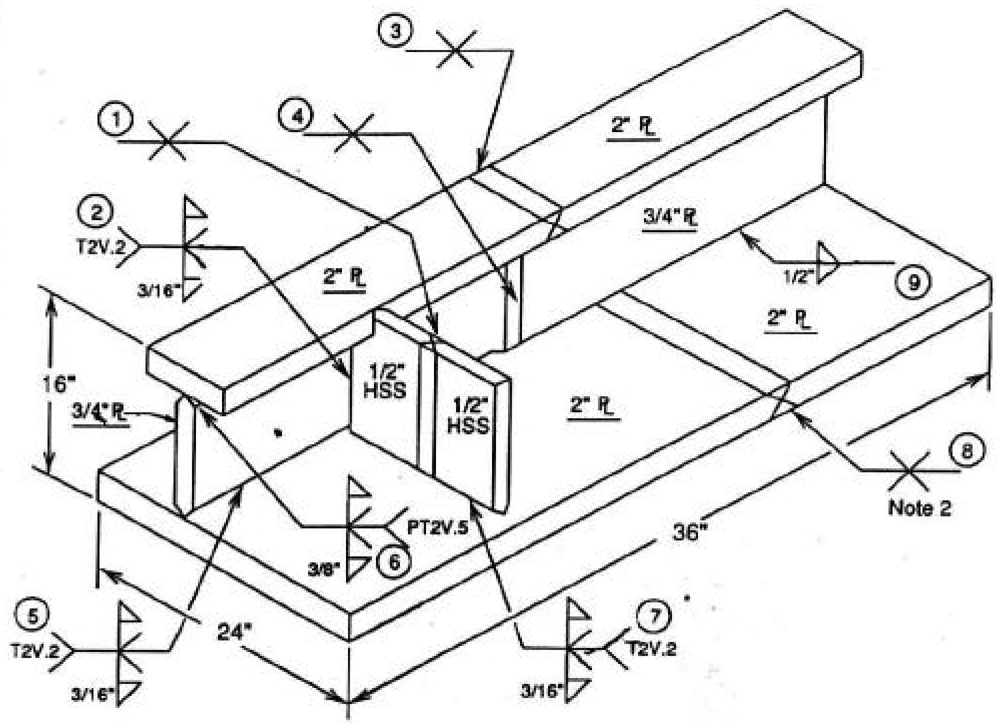


Figure 4-9 Underside of Diffraction EMAT Sensor for Surface Inspection of Welds

Figure 4-10 Wear Resistant Havar® Cover on EMAT Sensor

GENERAL DYNAMICS *Electric Boat Division*	**TECHNIQUE SHEET**	WP: dummy REV: 2 Page: of



NOTES

1. All material is HY-100 except as noted.
2. One side welded with MIL-120S-1, heat no, 120024, Spray GMA without preheat.

JOINT NUMBER ○	PROCESS AND PROCEDURE NEAR/ARROW SIDE	PROCESS AND PROCEDURE FAR SIDE
1	SMAW S01J09	SMAW S01J09
2	SMAW Y10M13	PGMAW Y10J19
3	SMAW Y10M03	PGMAW Y10M39
4	SGMAW Y10M40	PGMAW Y10M39
5	SMAW Y10M03	SGMAW Y10M40
6	PGMAW Y10M39	SGMAW Y10M40
7	SGMAW Y10M12	PGMAW Y10J19
8	SGMAW Y10J22	SAW Y10M07
9	SMAW Y10M03	SMAW Y10M03

Figure 4-11 Welding Techniques Used to Fabricate EB Mockup

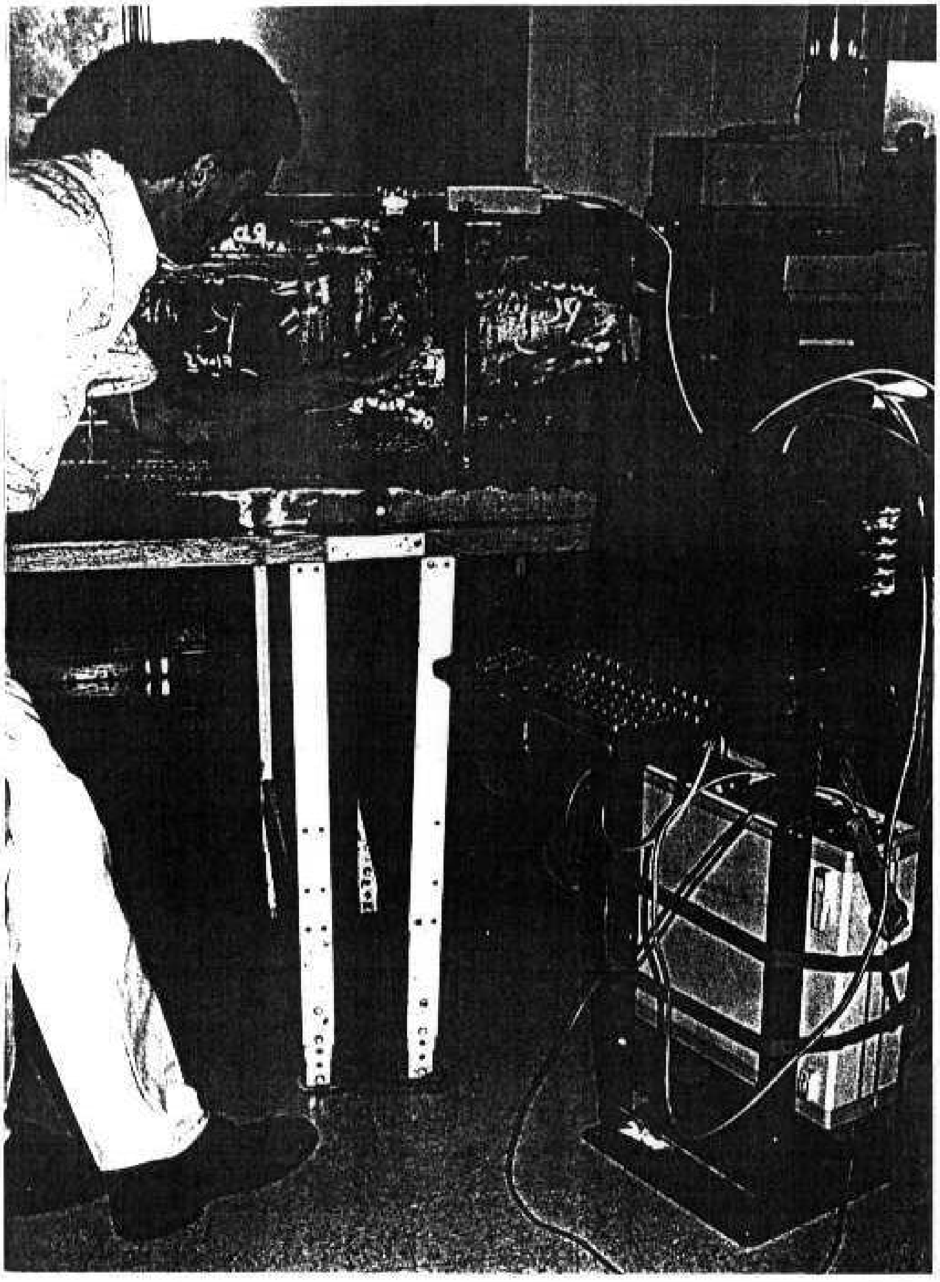


Figure 4-12 EB Supplied Mockup Undergoing Evaluations with Diffraction Sensor

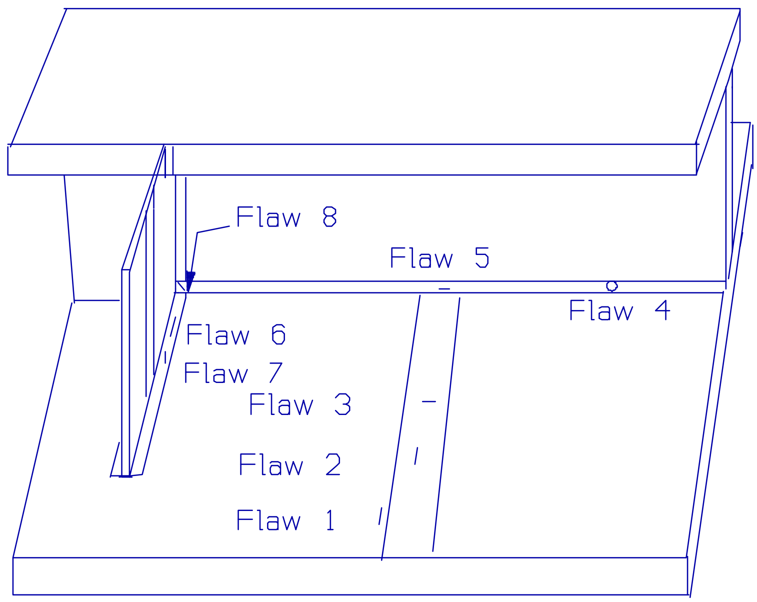


Figure 4-13 Flaw Locations in EB Supplied Mockup

Flaw #	Flaw Type	Weld Type	Flaw Location	Orientation	Length	Depth
1	notch	SAW/butt	toe	axial	0.126"	0.055"
2	notch	SAW/butt	crown	axial	0.090"	0.058"
3	notch	SAW/butt	crown	transverse	0.100"	0.062"
4	hole	SMAW/fillet	crown	NA	0.124" dia.	0.062"
5	notch	SMAW/fillet	crown	axial	0.109"	0.059"
6	notch	SMAW/fillet	crown	axial	0.113"	0.062"
7	notch	SMAW/fillet	crown	transverse	0.115"	0.061"
8	notch	SMAW/corner	crown	axial	0.104"	0.051"

Table 4-1 - Description of Flaws in EB Supplied Mockup

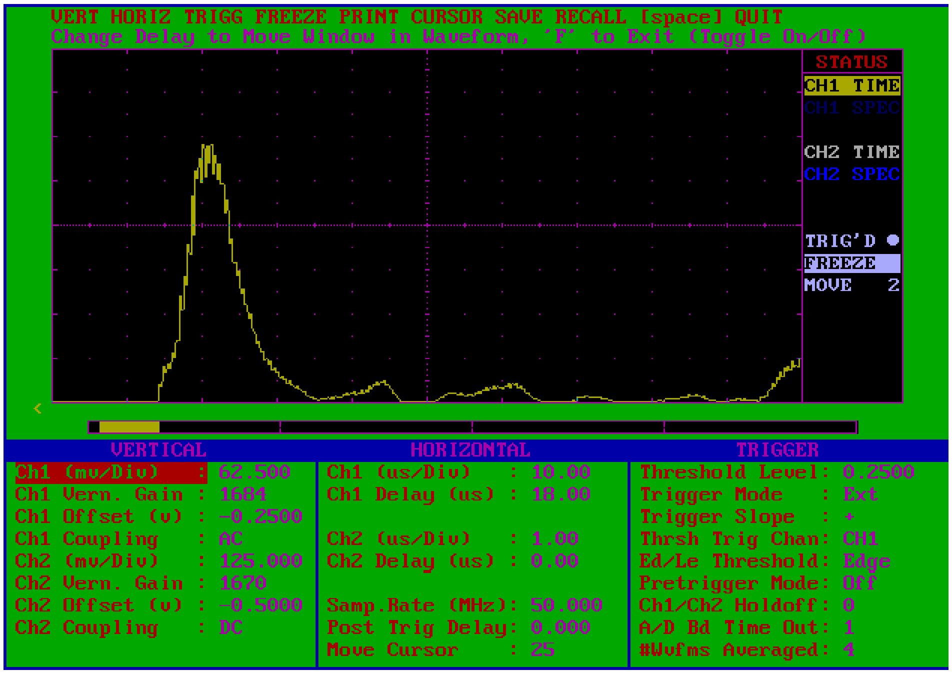


Figure 4-14 Response to Flaw 1 in EB Supplied Mockup

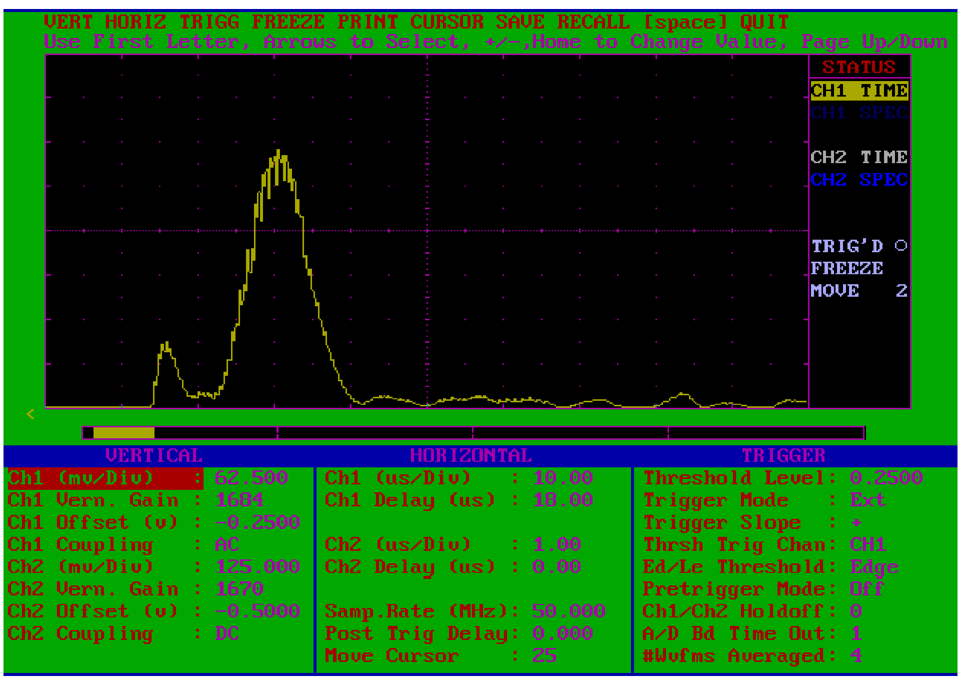


Figure 4-15 Response to Flaw 2 in EB Supplied Mockup

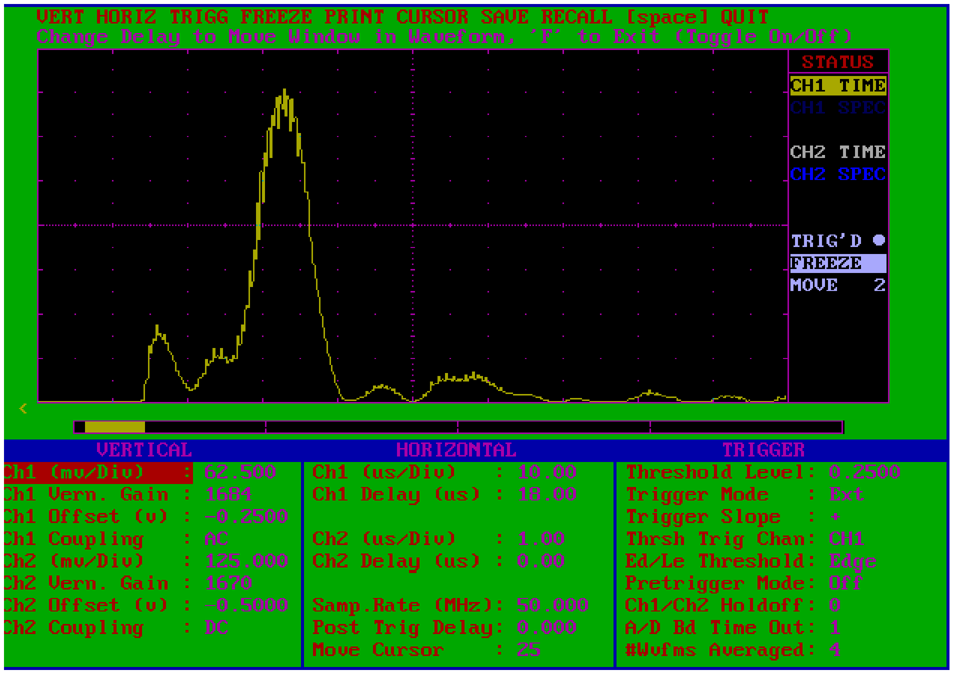


Figure 4-16 Response to Flaw 3 in EB Supplied Mockup

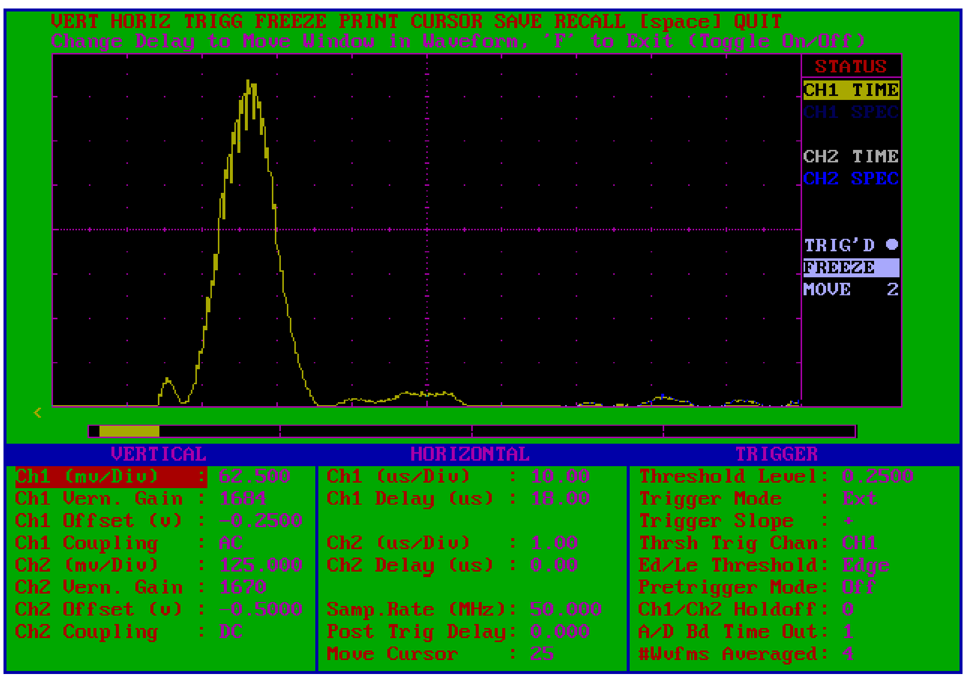


Figure 4-17 Response to Flaw 4 in EB Supplied Mockup

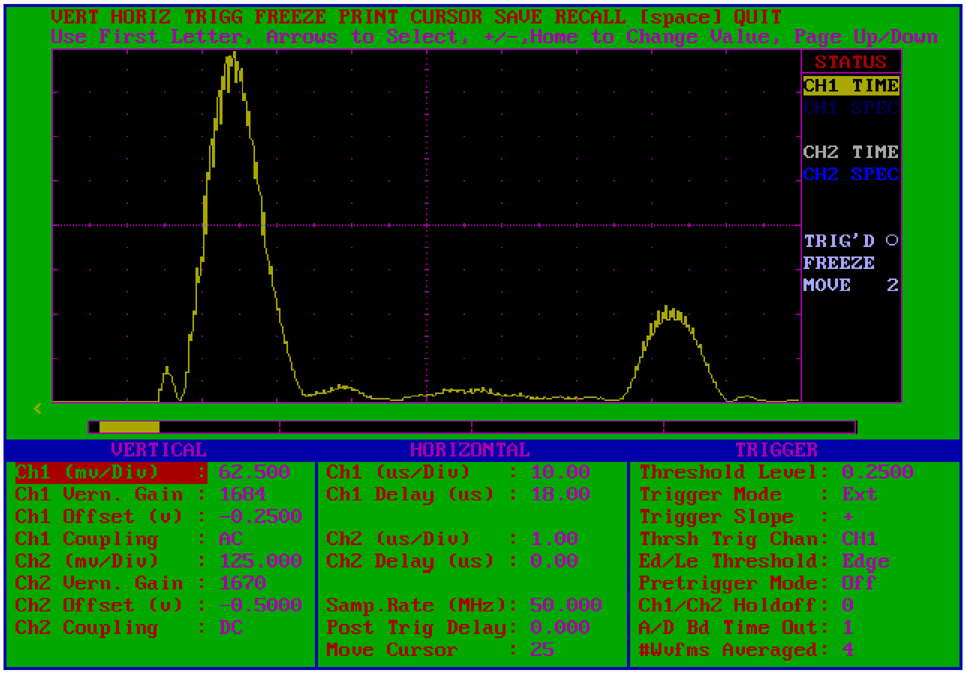


Figure 4-18 Response to Flaw 5 in EB Supplied Mockup

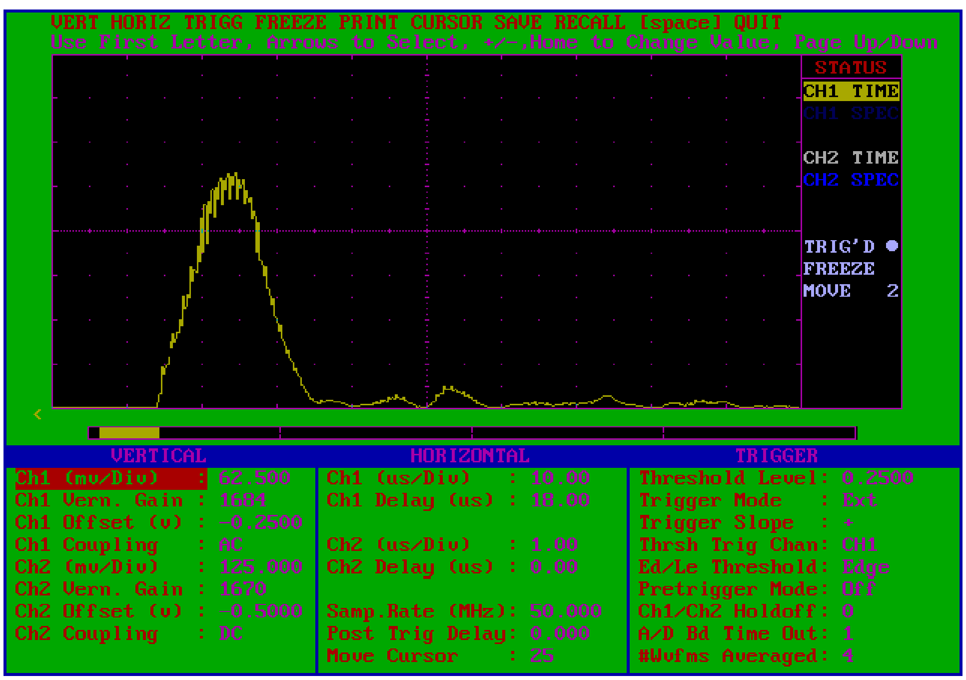


Figure 4-19 Response to Flaw 6 in EB Supplied Mockup

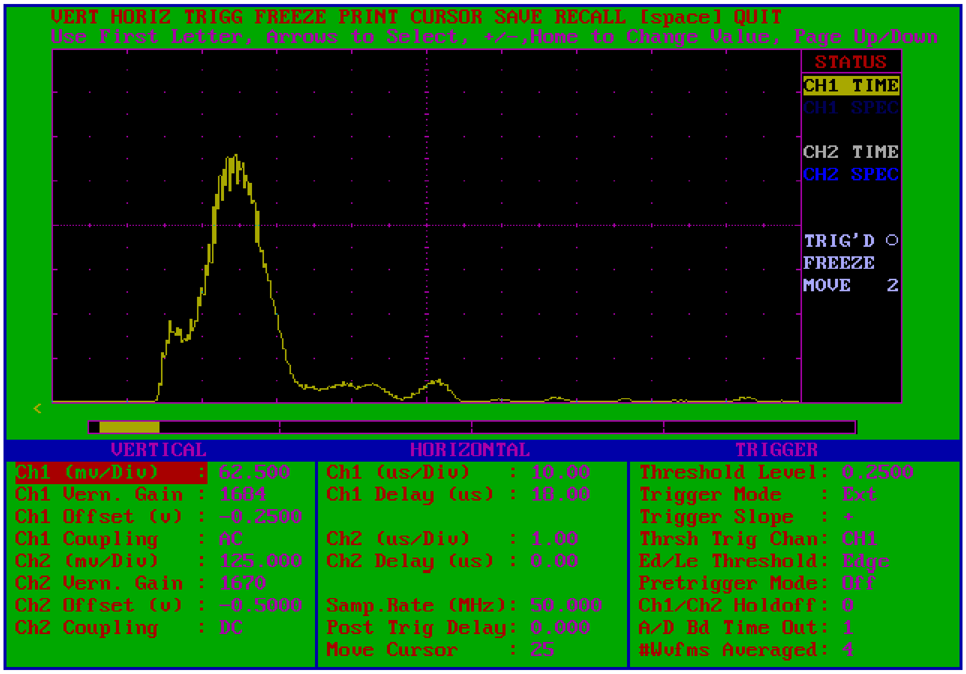


Figure 4-20 Response to Flaw 7 in EB Supplied Mockup

4.3.3 Concept design for production hardened diffraction sensor

The production EMAT probe incorporates characteristics not found in the prototype probe. The production probe is intended to simplify probe use and ease maintenance, while, at the same time, improve probe durability. The features that are improved to accomplish this include, 1) the EMAT coil, 2) the wear face, 3) the connector, and 4) the angle adjustment of the EMAT coil. The probe is intended for hand held, manual use, though it could easily be adapted to a mechanized scanning device. The probe is described in general below, followed by a description of the new attributes.

The probe is a permanent magnet EMAT sensor measuring about 3.25" long by 1.75" wide by 1.80" tall and weighing about 0.7 lb. This is approximately the same size as a 1" ultrasonic transducer/wedge combination. The main parts of the probe include 1) the EMAT coil, 2) a permanent magnet, 3) a wear face disk, 4) a carriage with rollers, 5) a rugged connector, and 6) a housing to which all other items attach. Various views of the production sensor concept are shown in Figure 21.

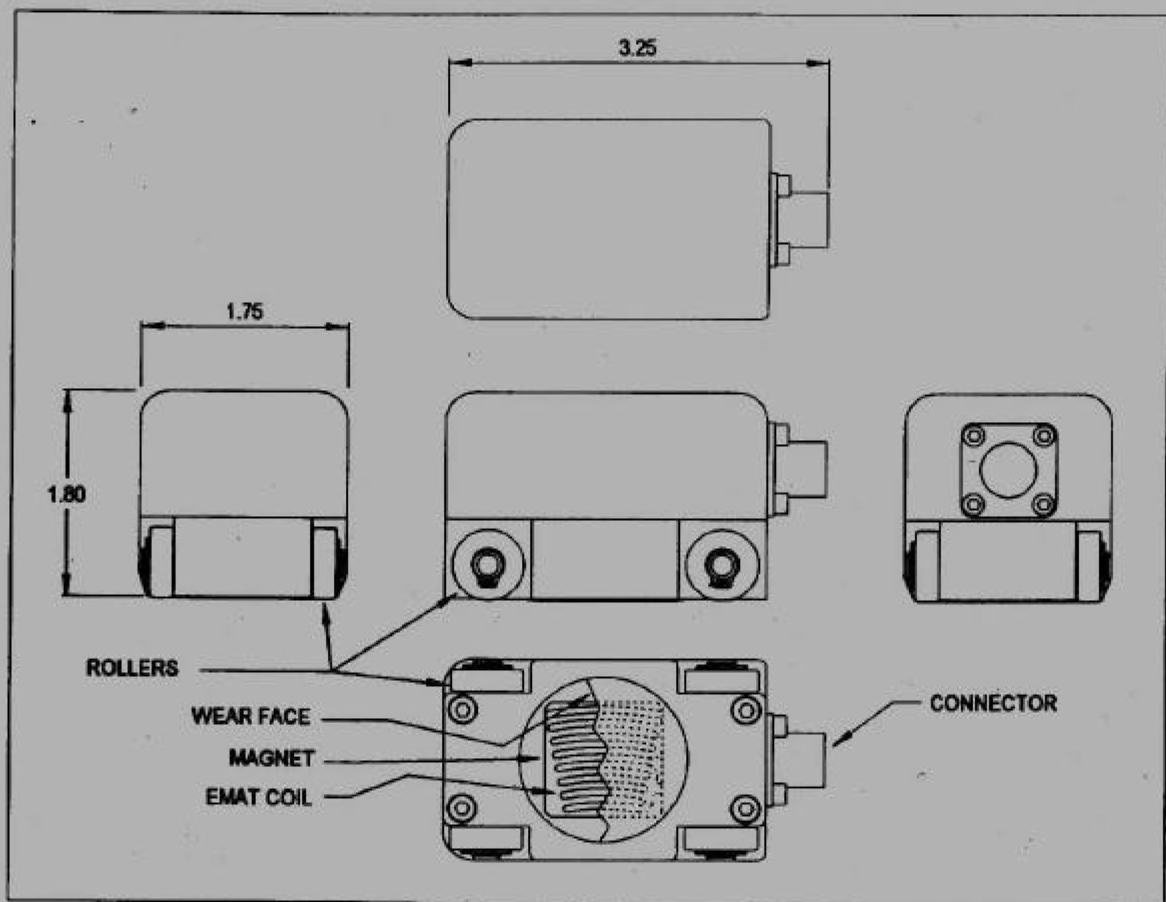


Figure 4-21 Production Sensor Design Concept (units in inches)

4.3.3.1 EMAT Coil

The coil is a focused meander coil (1MHz), pitch/catch or pulse echo, laid out to fit the 1" x 1" area of the magnet face. The coil folds around the magnet and is taped into place, leaving copper pads exposed for the contacts that are wired to the connector in the housing. It will include a cover coat of 0.0005" Kapton[7] so that no installation prep is necessary. The EMAT has a compliant backing that assures contact of the coil and wear face to the work surface in order to minimize and maintain uniform liftoff.

4.3.3.2 Magnet

The magnet will be a 1.0" by 1.0" by 1.0" neodymium iron boron (NdFeB) of energy product grade 48 MGO. The magnet will be a simple cube, though some corners will be chamfered. The magnet will be glued to a ferromagnetic retaining plate that is pinned into two shroud pieces that allow the magnet to rotate within the housing.

4.3.3.3 Wear Face

The wear face is a 0.002" thick metal disk (Havar[7]) that gets captured in the carriage by compression from the shroud pieces. The metal is selected to give good wear properties without significantly inhibiting the EMAT signal. The mechanism for mounting the wear face in the carriage provides for easy removal of stray metallic particles which may be attracted to the magnet.

4.3.3.4 Carriage

The carriage includes a black anodized aluminum frame with front and rear shafts. Each shaft supports two stainless steel sealed ball bearings for rollers. Because of the attractive force of the permanent magnet, the rollers are essential to allowing the probe to move easily across the weld area to be inspected. Metal rollers are best to control standoff. When assembled to the housing with four socket head machine screws, the carriage captures the EMAT coil, magnet, and wear face components. Since the probe is designed to roll adjacent to a weld, the carriage frame design allows the EMAT coil to be located close to the weld.

4.3.3.5 Connector

The EMAT coils will be replaceable without soldering. This is accomplished by using spring contacts mounted in the housing so as to contact the exposed pads on the EMAT coil. The spring contacts are wired to a rugged, compact, quarter-turn, 4 pin MS style connector. The connector is mounted to the backside of the housing, though a top or side mounted version could also be produced. Since the spring contacts and connector

are both mounted to the housing, no unwiring is required when the probe is disassembled for wear face replacement or other repair.

4.3.3.6 Housing

The housing will be black anodized aluminum and is constructed from a minimum number of parts to improve precision, durability, and appearance. Fillets and chamfers are used to enhance appearance and for ergonomic purposes. The housing includes a pin feature for "factory" adjustment of the EMAT coil angle. A pin is installed in one of 6 holes in the housing, then mated with one of 16 holes in the shroud surrounding the magnet. A redundant pin is also installed in a likewise redundant set of holes. The actual hole locations are determined by testing the probe on a calibration standard and selecting an optimum adjustment. The probe adjustment can be set at 0^0 or from 14^0 to 46^0 in 1^0 increments. Other angles are possible with design changes. Sectional views through the housing at several locations are shown in Figure 22.

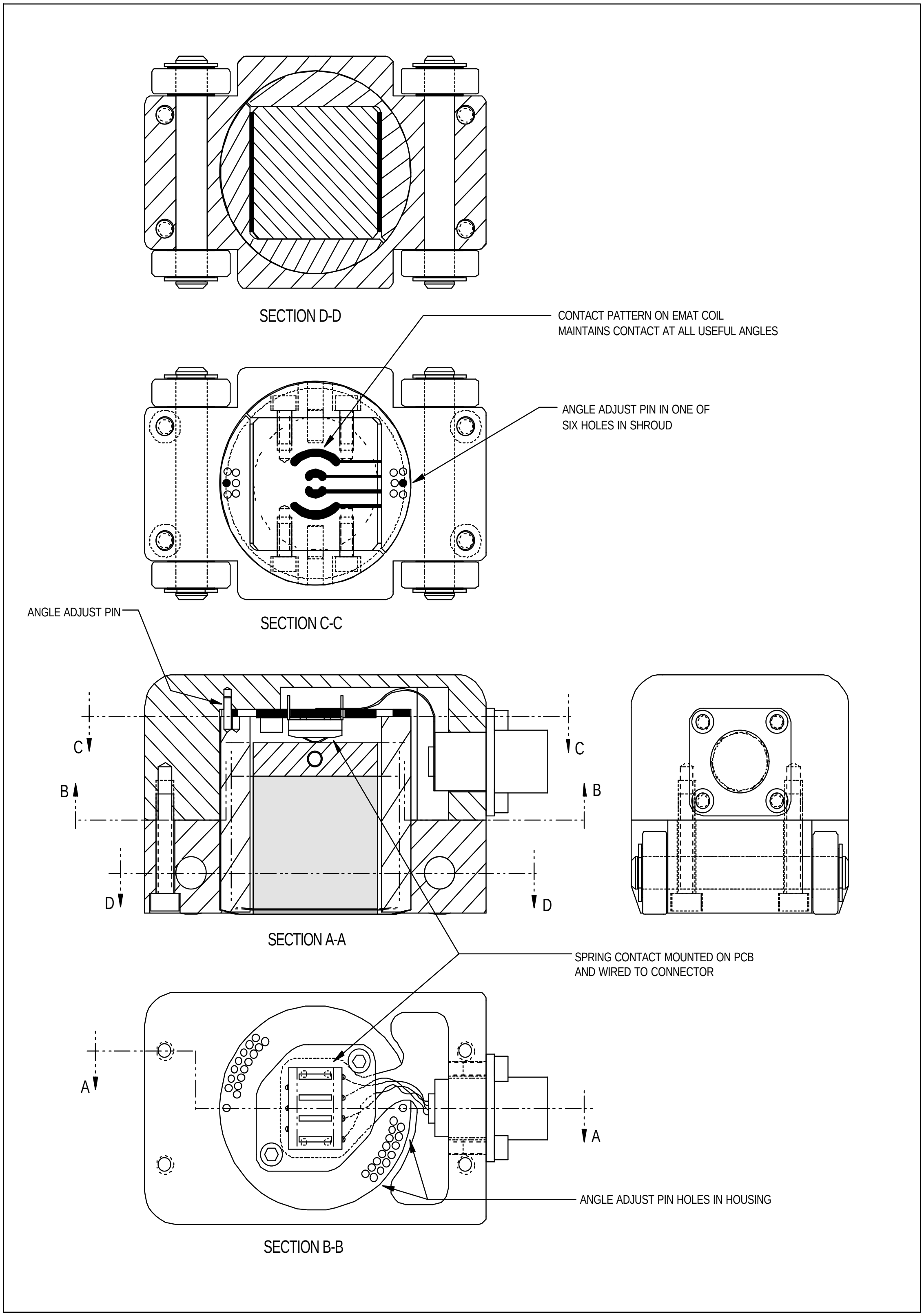


Figure 4-22 Sectional Views of the Production Sensor Concept

4.4 CONCLUSIONS

- Two methods, one based on diffraction and the other on attenuation, have been developed for surface inspection of welds. Both tests can be used for rapid and reliable subsurface and surface-breaking flaw detection in structure type welds.

- All EMAT evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

Zig-Zag (Attenuation Technique)

- 2MHz surface waves 1/2" x 1/4"permanent magnets (NdFeB)/unfocused coils

- Excellent high speed test of mechanized welds/base metal

- Not suitable for rough welds or complex geometries

- Operates on painted surfaces (up to 15 mils thick)

- Capable of detecting surface-breaking and subsurface flaws at all orientations

Diffraction Technique

- EB supplied welded mockup with complex geometries (corners, tees)

- 0.125"L X 0.060"D flaws in various locations/orientations

- 1MHz focused surface waves/1 inch cube NdFeB permanent magnet sensor

- A superior wear face material has been identified - Havar[7] (Co/Ni/Cr alloy)

- All flaws were detected with good S/N except in corner. Corner flaws are not detectable due to the energy reflected from corner geometry back to sensor.

- Best results on butt welds (S/N > 20:1)

- Good results on "rough" fillet welds (S/N >15:1)

4.5 RECOMMENDATIONS

- Both EMAT surface inspection methods (diffraction and attenuation) are considered to be ready for shipyard implementation. Discussions with NAVSEA indicate that individual yards will be expected to make their cases for use of the technique for replacement of conventional surface inspection methods, e.g., MT and PT. In those cases where NAVSEA or applicable manufacturing code does not stipulate NDE requirements or prohibit the use of EMAT for surface inspection of welds/base metal, it is recommended that EMAT be pursued. There are commercial manufacturers of EMAT probes/electronics which can provide production systems, including spare parts, warranties, and service. MTI is prepared to assist the yards in implementation of the EMAT technology for surface inspection.

- Complete current phase of SP-7 project, focusing on piping welds.

- Get additional samples of welded pipe from EB and/or Puget.

- Complete internal programs (phased array EMAT system evaluations on JRay McDermott (JRM) offshore lay barge project) to leverage volumetric weld inspection technology for the SP-7 panel.

- Maintain data base on JRM project (EMAT results vs. RT) and attempt to get access to Shaw Pipeline Services (vendor of current UT system for piping girth weld inspection system) data base (UT vs. RT).

5.0 PHASED ARRAY EMATS FOR PIPING WELDS

DEVELOPMENT OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS) FOR SURFACE/VOLUMETRIC INSPECTION OF WELDS

- FINAL SUMMARY REPORT -

INVESTIGATION OF THE USE OF PHASED ARRAY EMATS FOR CIRCUMFERENTIAL PIPING WELDS

PREPARED BY

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January 17, 2000

PREPARED FOR

HALTER MARINE GROUP, INC.
GULFPORT, MS
AND
NAVAL SURFACE WARFARE CENTER

HMGI PURCHASE ORDER NO. 2228
PROJECT NO. 7-96-1
MTI CONTRACT NO. CRD - 1355

5.1 SUMMARY

This project involves the development of EMAT techniques for both surface and volumetric weld inspection, specifically for shipyard use. It is a continuation of earlier programs sponsored by the SP-7 Welding Panel of the National Shipbuilding Research Program and General Dynamics - Electric Boat Division (EB) through Knolls Atomic Power Lab (KAPL). This report documents the results of NSRP project 7-96-1 Phase 2, Tasks 1 "Procure Representative Welded Samples" and Task 2 “Investigate the Use of Phased Array for the Inspection of Circumferential Piping Welds”.

In Phase 1 of the project a very promising technique was developed for surface inspection of welds using EMATs. This EMAT inspection technique has the potential to replace penetrant testing providing much faster inspection rates, documented inspection results, and eliminating the use of hazardous chemicals. A promising EMAT based technique for the volumetric inspection of welds has been developed that is the subject of this report. This technique is based on the use of phased array EMATs to perform volumetric weld inspection. The ability to detect and size weld defects with this technique to within +/- .04" has been demonstrated. This technique has the potential for replacing radiography and conventional ultrasonic inspection of welds. Fully implemented, it has the potential to perform high-speed automated volumetric inspection of welds without the need for a couplant. The system would be very flexible allowing operation on different wall thickness components and different weld configurations with only software configuration changes.

A shear horizontal wave phased array EMAT system developed by McDermott Technology, Inc. was used to conduct the investigation. The results of the investigation indicated that:

- The phased array system was capable of focusing the SH wave beam to a focal spot of approximately 2 mm (.080") by 2 mm (.080") in magnetic steels.

- The system was capable of electronically sweeping the focal spot and determining the through wall height of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”).

- The system was capable of determining the circumferential length of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040”) by moving the focused beam testhead along the weld and monitoring the defect signal as a function of position.

- This approach to weld testing appears to be applicable to magnetic steel pipe diameters from less than 5 mm (2”) up to flat plate.

- The system was capable of detecting lack of root penetration defects in magnetic steel welds with excellent signal to background noise, due to the absence of mode conversion with the SH wave mode.

- Lack of fusion at the weld cap was readily detected with a surface skimming (90°) SH wave in a magnetic steel weld using the phased array EMAT system.

- A rapid drop in angle beam EMAT sensitivity with frequency for nonmagnetic high-resistivity metals makes it impractical to operate at frequencies high enough to provide adequate resolution for sizing the through wall height of weld defects in these metals.

5.2 BACKGROUND

A comprehensive introduction and background for the project is given at the beginning of this final report.

5.3 INVESTIGATION OF THE USE OF PHASED ARRAY EMATS FOR CIRCUMFERENTIAL PIPING WELDS

5.3.1 Phased Array EMAT System Background

The use of fracture mechanics analysis and fitness for purpose criteria allows a method for establishing acceptable volumetric flaw sizes in welds that encompasses both flaw through- wall height and flaw length. In order to utilize these criteria in making accept-reject decisions, an NDE inspection method is required that can provide characterization of the flaw's length and through wall height with reasonable accuracy. If the NDE method used is not capable of providing flaw through wall height information, and provides only flaw length information, the flaw must be evaluated as having the maximum through wall height in making accept-reject decisions. This causes unnecessary repairs or component replacement, resulting in lost productivity and increased costs. In many applications the flaw characterization information must be made available in near real time for it to be useful.

An emerging ultrasonic inspection technology for industrial NDE is the use of ultrasonic phased array ultrasonic sensors and systems. Phased array technology allows the generation of an ultrasonic beam with the possibility of using software to set the beam parameters such as angle, focal distance, and focal point size through software. The ability to dynamically change the properties of the probe provides many new possibilities for ultrasonic inspections. For example it is possible to quickly perform a linear scan of a region of a part without having to move the probe. It is also possible to vary the angle of the beam without changing the probe, allowing multi-angle inspection of the part from a single point. Phased array technology allows the replacement of multiple probes and even mechanical scanning apparatus by a single phased array transducer.

EMATs are a non-contact method of generating and receiving ultrasound in conductive and magnetic materials. Typically a wire coil is used to set up dynamic eddy currents and magnetic fields in the surface of the material. A static or quasi-static magnetic field is also set up in the surface of the material using permanent magnets, electromagnets, or pulsed electromagnets. Lorentz and / or magnetostrictive forces are generated in the surface of the material due to the interaction of the dynamic fields and the static fields. These dynamic surface forces generate ultrasonic waves in the material. A reciprocal process allows ultrasonic waves striking the surface to be detected using these same transducers. Using different combinations of magnet and coil configurations, a wide variety of wave types and beam characteristics can be achieved. Being non-contact, EMATs are useful in automated ultrasonic testing (UT) systems. They can also be used for inspecting materials at elevated temperatures and have been used at temperatures in excess of 2000° F in some applications. Since ultrasound is generated and received directly in the surface of the part being inspected, wedges or ultrasonic delay lines are not required, and the errors produced by time delay variations in these components of conventional ultrasonic testing are eliminated. Typically EMAT coils are fabricated using photo-etching techniques resulting in nearly identical characteristics from transducer to transducer.

One of the most promising advantages for using EMATs in weld inspection applications is the ability to generate shear (SH) horizontal waves in a manner practical for high speed scanning. A transient line force in the surface of a material, with the force directed along the line, produces SH waves with uniform amplitude and constant phase for all angles in a plane normal to the line. SH waves reflect from surfaces parallel to the shear polarization with equal amplitude and without mode conversion for all angles of incidence. As a practical matter this results in several potential advantages for inspecting welds. Any beam angle can be used to inspect the weld from 0° to 90° (note: angles given are with respect to the radial or through-wall direction perpendicular to the surface). Corner-type reflectors reflect SH wave beams with equal amplitude for all angles of incidence whereas SV wave beams employed with conventional UT experience deep nulls in the reflectivity at incidence angles of around 30° and 60° due to mode conversion. A surface skimming (90°) SH wave beam can be used to interrogate the weld for lack of fusion at the cap or crown (outer surface) of the weld that is not sensitive to the excess weldment or reinforcement in the weld cap.

In order to address the need to characterize weld flaws in near real time, McDermott Technology has developed a phased array EMAT system for the inspection of welds. This system combines the advantages of phased array technology with the advantages of using EMATs to create a unique weld inspection tool. The system is capable of changing beam characteristics at rates up to 20,000 times per second, using up to 1,024 different configurations. For the inspection of magnetic materials such as carbon steel, the EMAT head consists of a pulsed magnet and flexible printed circuit EMAT coil driven by radio frequency (RF) currents. The system operates at an ultrasonic frequency of 5 MHz allowing high-resolution time of flight measurements.

Beam angle, focal point, and focal width in the vertical plane (perpendicular to the surface of the pipe) is determined using well-known phased array principles. Focussing the EMAT generated beam in the horizontal plane (parallel to the surface of the pipe) is accomplished by constructing the EMAT coils as an array of circular arcs centered on the desired focal point. The focal width is determined by well-known relationships between aperture (arc length), distance to the focal point, and ultrasonic wavelength. Using a combination of geometrical and phased array focussing, a focal spot approximately 2 mm in diameter has been obtained, allowing sizing of planar defects such as lack of sidewall fusion in welds.

Welded plates and tubes are first prepared by cutting the surfaces to be joined together in specific patterns. For example, manually welded component ends are typically cut with a 30° bevel (with respect to the surface normal) for most of the thickness of the plate with a short vertical cut at the bottom of the components in the region known as the root of the weld. Obtaining complete fusion between the weld material and the component surfaces is of primary concern. By electronically scanning the focused phased array EMAT beam along this fusion line, lack of fusion areas can be detected and sized. In operation the EMAT probe head can be scanned next to the weld while monitoring the probe position along the length of the weld using an encoder. At predetermined distance increments the phased array system is triggered and executes a series of ultrasonic interrogations of the weld, using configurations stored in the phased array instrument.

The flexibility of the phased array system coupled with SH wave generation allows a wide range of inspections with different beam angles, focal points, and focal widths to be performed. A phased array scan plan might include a focused sweep of the sidewall fusion line, inspections of the weld volume, interrogation of the root of the weld for lack of penetration, and inspection of the cap of the weld for "undercut" or lack of fusion at the upper surface. Executing a scan plan where 20 different inspections are performed at 1 mm intervals along the weld, at a scan rate of 200 mm per second (approx. 8" per second), requires a firing rate of 4 kHz, well below the 20 kHz maximum firing rate of the phased array system. Another mode of operation that can be envisioned is operating in a detection only mode until a defect is located, then automatically reconfiguring the system to perform a high resolution scan of the flawed region to provide characterization of the defect. This would allow very rapid scanning of defect free areas, and high-resolution inspection of flawed areas.

A three-dimensional software simulator has been developed which allows the ultrasonic behavior of the phased array EMAT to be modeled. Arbitrary time-dependent excitation of the EMAT elements can be modeled and "snapshots" of the simulated ultrasonic wave packets obtained. Modeling has indicated that the current EMAT probe is capable of a focal spot as small as 1 mm in through wall height by 2 mm wide in the direction of the length of the weld. In many applications such high resolution is not required and a larger focal spot size can be used which increases the depth of focus for a given wavelength. The focal spot size can be tailored to meet the inspection requirements during the design of the EMAT probe and in configuring the phased array instrument.

The EMAT probe utilizes a flexible EMAT coil with a compliant backing that allows it to conform to curved surfaces such as pipe. Interchangeable pole pieces on the pulsed magnet allow the probe to be rapidly reconfigured to operate on different pipe diameters. The initial probe design covers from flat plate to pipe down to 14 cm (5.5") in diameter. Smaller diameters can be accommodated with modifications to the pulsed magnet. A pulsed magnet SH wave EMAT probe has recently been developed for operation on 44.5 mm (1.75”) diameter pipes. The flexible coils are relatively inexpensive when produced in large quantities. A thin flexible wear surface covers the EMAT coil and is designed for quick replacement. The flexibility of the probe and phased array system allow it to be used in a wide range of inspection applications.

This probe is useful for testing on ferritic steels having good magnetostrictive properties. This includes most of the common grades of structural steel and magnetic stainless steels. Testing of dissimilar metal welds can be accomplished if inspection from only the magnetic material side of the weld is adequate.

For inspecting nonmagnetic metals, SH wave EMAT arrays using permanent magnets can be constructed. However the permanent magnet arrays are not flexible and must be contoured to match the surface to be inspected [1]. In addition many of the nonmagnetic materials employed in piping are metals that have relatively poor conductivity making them poor candidates for inspection using EMATs operating at high frequencies. These materials include austenitic stainless steels, Inconel, and nickel copper alloys. Recent efforts at developing inspection techniques for nuclear piping welds in the electric power generation industry have employed phased array permanent magnet SH wave transducers operating in the frequency range of 1 MHz and lower [1]. Inspections performed with these transducers have typically been aimed at the detection of defects and the

1 J. Landrum and D. MacDonald, “Application of EMAT Technology to Piping NDE”, EPRI 7th Annual NDE Issues Meeting, Charleston, S.C., July 9, 1997.

measurement of the length of the defects, but not the measurement of the through wall height because of the low frequencies employed.

Investigations at MTI have shown that as the ultrasonic frequency of operation is increased the sensitivity of periodic permanent magnet array SH wave EMAT probes drops very rapidly. As the frequency is increased smaller permanent magnets of alternating polarity must be used in the EMAT. The drop in received signal amplitude due to liftoff between the magnets and the surface of the part, is an exponential function of the liftoff divided by the magnet to magnet spacing. As the magnet size and therefore magnet to magnet distance decreases, the sensitivity reduces dramatically for a given magnet to surface liftoff. A second reduction in sensitivity occurs when the electromagnetic skin depth of the induced dynamic electromagnetic fields becomes comparable to the ultrasonic wavelength. The ratio of skin depth to wavelength varies as the square root of the frequency, resulting in a reduction in sensitivity for EMAT operation in poorly conducting metals at higher ultrasonic frequencies. The effects combine to make it impractical for EMAT probes operating at higher frequencies to be used to inspect these materials and provide adequate resolution of the through wall height of weld defects at this time.

5.3.2 Phased Array EMAT Tests For Welds In Magnetic Steel

An EMAT phased array probe has been developed to allow the inspection of welds in magnetic materials. The probe was designed to have the following characteristics:

Beam angle range:	40° to 90°
Focal width in through wall direction (40° to 70°):	2 mm (.08")
Focal width along length of weld:	2 mm (.08")
Path length resolution from time of flight measurement:	+/- 0.5 mm (.02")

To meet these objectives for pipe wall thicknesses up to approximately 25 mm (1”), a 32-element EMAT SH wave array has been fabricated. Element to element spacing is approximately 2 mm for an overall length of 6.4 cm. Figure 5-1 shows a diagram of the EMAT coil and probe. The EMAT coil is an array of circular arcs centered on the desired focal point. The focal point is chosen to be at the center of the region of the weld to be inspected. The focal depth is such that the beam remains focused over the complete area to be inspected. Each element is comprised of a two-loop meander coil. By using a meander coil with two loops instead of a single loop for each element, the sensitivity of the system can be increased substantially at a cost of reducing the range of angles that can be covered. The two-loop meander coil that comprises each of the 32 elements is designed to have a maximum response at the midpoint of the desired range of angles, in this case 60°. The radiation pattern for the individual two-loop elements has been modeled and measured on a half-cylinder of steel for two-loop EMAT coil. Figure 5-2 shows a comparison of the model predicted and measured radiation patterns. Good agreement was obtained. The signal amplitude is within 6 dB of the maximum at 60° over a range of 40° to 90°. The steep drop in amplitude below 40° serves to reduce any side lobes generated at smaller angles that might reverberate through the thickness of the metal. Figure 5-3 shows a “snapshot” of the intensity of the simulted wave packet for a 45°-focused beam as it passes through the focal point. A –6 dB focal spot size of approximately 2mm is shown in both the through wall direction (top image) and parallel to the surface (bottom image).

The complete phased array EMAT system is comprised of a commercially available phased array UT instrument, 32 high power EMAT pulsers, magnet pulser, testhead preamplifiers, testhead transducer matching electronics, EMAT test head, interconnecting cables, and computer. Photographs of the system are shown in Figure 5-4. The computer provides system control, data acquisition, and data display. An online testing configuration might include two test heads looking at the weld from both sides.

In order to test the resolution of the phased array EMAT system, lack of sidewall fusion was simulated by drilling a 3 mm (.12") flat-bottomed hole in a 15.2 cm (6.0") diameter pipe having a wall thickness of 18.3 mm (.72"). The hole was drilled such that the flat-bottom surface makes a 30° angle with respect to the surface normal. The phased array EMAT system was programmed to perform an electronic scan of the simulated fusion line in approximately 1 mm (.04") increments, using a focal spot approximately 2 mm (.08") in diameter. Figure 5-5 is the resulting B-scan image of the 3 mm (.12") diameter hole flat bottom. Signal amplitude and time of flight measurements were taken at each increment. The location of the reflector was calculated from the known beam angle and time of arrival. The reflector locations are plotted on a diagram (Figure 5-6) showing the pipewall and flat-bottomed hole for amplitudes within 6 dB of the maximum amplitude reflection. Testing reflector length resolution in the direction along the weld by translating the probe past the 3 mm (.12") flat-bottomed hole produces similar results, within the +/- 1 mm (.04") resolution requirements for the probe design. Testing on a number of other simulated defects has provided similar results verifying that the phased array EMAT system is capable of the designed resolution.

Testing on samples with actual weld defects have provided similar results. Figure 5-7 depicts the cross section of a magnetic steel pipe weld test sample produced at MTI’s welding labs in Alliance, Ohio. Several defects were induced in the weld. Figure 5-8 shows the B-scan created by an electronic sweep of the sidewall fusion line in the sample with a 60° focused beam in 0.5 mm (.02") increments using the phased array EMAT system. The B-scan shows the image of a lack of sidewall fusion defect. The image indicates the defect's through wall height to be approximately 5.1 mm (0.2"). A conventional hand scanned 9.5 mm (.375") x 9.5 mm (.375") unfocused 5 MHz conventional shear wave probe was also used to roughly confirm the EMAT through wall height estimate.

The use of SH waves for the detection of lack of penetration at the root and lack of sidewall fusion at the cap was tested using the carbon steel weld sample. A lack of root penetration defect was created in the weld sample. Figure 5-9 is the A-scan showing the reflected signal from this lack of penetration defect using the EMAT phased array system to generate a 60° focused beam directed at the root. Excellent signal to background noise has been observed for these types of defects using SH waves. Figure 5-10 shows a comparison of the corner reflection coefficient for SH waves and SV waves in steel vs. incident angle. It appears that for incident angles in the neighborhood of 60° to 70° the SH waves perform much better than SV waves for distinguishing between actual lack of penetration at the root and reflections from excess weldment protrusions.

A unique use of SH waves for detection of lack of sidewall fusion at the cap was tested using the carbon steel weld sample. Figure 5-11 is an A-scan of a lack of fusion defect at the cap of the weld using a surface skimming (90°) SH wave.

Above approximately 70° it is not feasible to obtain a highly focused beam in the through wall direction because the effective aperture size of the sensor decreases severely. The beam width is given approximately by:

Beam width ≅ (Focal Distance) x (Wavelength) / ((Array Length) x Cos(Beam angle))

At higher beam angles the cosine of the beam angle becomes very small requiring an impractical array length in order to obtain a given focal spot size. Sizing in the through wall dimension is diminished for these higher angles.

The ability to generate and receive ultrasonic beams with angles from 40° to 90° degrees has been found to be useful for tandem operation. In tandem operation one set of elements is used to transmit a beam at a particular angle, while another set of elements is used to receive the reflections at a different angle. A unique advantage of phased array systems is that the transmitter and receiver elements can overlap (transmit and receive can share elements). Oftentimes for conventional UT tandem operation the reflected signal must bounce off of the ID surface before being detected by a separate receiver transducer. The extra bounce off of the ID surface is undesirable. By using EMATs and SH waves it is possible to detect directly reflected signals at high angles (such as 75° to 90°) eliminating the need to reflect from the ID surface in some cases. For example a 60° highly focused beam reflects from a 10° bevel lack of fusion defect at an angle of 80° which can be detected with the SH wave phased array EMAT. Sizing is accomplished by electronically scanning the highly focused transmitter beam through the weld volume.

Recently a pulsed magnet EMAT SH wave sensor has been developed for 44.5 mm (1.75") diameter 12.7 mm (0.5") wall tubing used for dissimilar metal weld testing. Results of testing using this sensor indicate that the phased array SH wave EMAT probe can be adapted to operate on tubes with diameters smaller then 2" and up to flat surfaces.

EMAT testing typically requires less surface preparation than conventional ultrasonic transducers due to the fact that for EMATs the ultrasound is generated directly in the surface of the metal. In conventional UT the ultrasound must be coupled into the surface of the metal through whatever might be on the surface. However, when operating at 5 MHz the EMAT coil must be maintained as close to the surface of the part as possible. This is accomplished with the phased array EMAT system by using a very thin wear surface between the metal and the EMAT coil. A layer, .025 mm (.001") to .075 mm (.003") thick, of a high-resistivity metal is typically used. The EMAT coil and wear surface are very thin and compliant. A silicon sponge rubber backing keeps the EMAT coil and wear surface held against the metal surface. Weld splatter next to the weld will cause the wear surface and EMAT coil to lift off of the surface, causing a localized loss of signal. In some cases the weld splatter may even damage the wear surface. It is necessary to remove any weld splatter next to the weld prior to testing. This is typically a requirement for conventional ultrasonic testing as well.

The first-of-its kind SH wave EMAT phased array system developed at MTI has several drawbacks that would need to be remedied in order for the system to be used in online testing. The electronic signal-to-noise ratio of the system is inadequate. Signal averaging has been employed in order to obtain sufficient signal-to-noise for most of the testing performed to date. This has limited the systems ability to perform high speed scanning and has made it difficult to detect the reflections from small volumetric defects such as porosity. The poor signal-to-noise ratio has been identified as very inefficient power transfer between the individual coils in the phased array EMAT and the remote electronics. Modifications to the system to overcome this problem have been devised. Testing was also limited by the lack of fully integrated phased array control, data acquisition, and display software. Fully automated and integrated software will be needed in order to take full advantage of the systems capabilities.

5.3.3 Phased Array Probe Design and Testing for Welds in Nonmagnetic Materials

The inspection of welds in austenitic stainless steel and other noisy materials has been a difficult problem for ultrasonic testing techniques. Studies have indicated that EMATs generating SH waves have a distinct advantage in inspecting these materials. A review of published literature on the use of phased array SH wave EMAT transducers for the inspection of nonmagnetic pipe welds used in the nuclear power generation industry indicate that they have been limited to use at frequencies of approximately 1 MHz and lower(1). This low frequency of operation severely limits the ability to detect and size the through wall height of defects in pipe welds. The use of higher frequencies is desirable in order for SH wave EMATs to be of practical use for inspecting welds in these materials.

An investigation into the sensitivity of periodic array SH wave EMATs for inspecting nonmagnetic, poorly conducting metals at higher frequencies has been conducted. This investigation has shown that as the ultrasonic frequency of operation is increased the sensitivity of these SH wave EMAT probes drops very rapidly. This is primarily due to two effects. As the frequency is increased smaller permanent magnets of alternating polarity must be used in the SH wave EMAT. The drop in received signal amplitude, due to liftoff, is an exponential function of the liftoff divided by the magnet to magnet spacing. As the magnet to magnet distance decreases the sensitivity reduces dramatically for a given magnet liftoff. Figure 5-12 shows the calculated relative signal amplitude for a periodic permanent magnet (PPM) 60° SH wave EMAT probe operating with liftoffs of 0.125 mm (.005”), .25 mm (.010”), 0.375 mm (0.015”), and .5mm (.02”) as a function of frequency. The metal is assumed to be ideal with infinite conductivity and no ultrasonic attenuation. Because periodic magnet array EMAT probes are rigid and the EMAT coil must be between the magnets and the metal surface, they typically are operated with magnet-to-metal surface gaps of at least 0.25 mm (.010") leading to a severe reduction in sensitivity at higher frequencies.

Most of the nonmagnetic materials used in piping have relatively poor electrical conductivity. A reduction in EMAT sensitivity occurs when the electromagnetic skin depth of the induced dynamic electromagnetic fields becomes a significant fraction of the ultrasonic wavelength. The ratio of skin depth to wavelength varies as the square root of the frequency, resulting in a reduction in sensitivity in poorly conducting metals such as nonmagnetic stainless steel, Inconel, and nickel copper alloys at higher ultrasonic frequencies. Figure 5-13 is a plot of the electromagnetic skin depth to wavelength ratio for 304 stainless steel and aluminum as a function of frequency. In order to measure the effect of frequency on the sensitivity of SH wave EMATs for poorly conducting materials the back wall signal amplitude of a 0° EMAT generated shear wave was measured as a function of frequency for an aluminum plate and 304 stainless steel plate. 0° shear wave EMATs are broadband devices capable of operating over a wide frequency range. The reduction in signal amplitude with increasing liftoff is not frequency dependent for 0° shear wave EMATs. Figure 5-14 is a plot of the signal amplitude for 304 stainless steel divided by the signal amplitude obtained in aluminum as a function of frequency. Aluminum is known to be a good conductor and serves as a good reference material. Figure 5-14 shows a reduction in the ratio of the signal amplitude for stainless steel to aluminum with increasing frequency. This is caused by the high resistivity of the stainless steel. The skin depth in the poorly conducting stainless steel becomes a significant fraction of the ultrasonic wavelength, resulting in reduced generation and reception efficiencies.

EMAT sensitivity is inversely proportional to the density of the metal. The signal amplitudes are much smaller in stainless steel than aluminum for all frequencies because stainless steel is much denser than aluminum. This is also true of many of the other nonmagnetic high-resistivity metals.

The signal reduction effects combine to cause the sensitivity to drop very rapidly above about 1 MHz. Our testing indicates that it is not possible to obtain sufficient sensitivity at the higher frequencies that are needed to provide defect through wall dimensions with reasonable resolution, using these EMATs.

Periodic permanent magnet probes are not flexible and must be constructed with magnets contoured to the curvature of the pipe to be inspected. The construction of these probes is relatively expensive, making the prospect of having several of these probes on hand to cover a given range of pipe diameters unattractive.

5.4 CONCLUSIONS

- The phased array EMAT SH wave system was capable of generating and steering SH wave ultrasonic beams over an angle of approximately 40° to 90° in magnetic steels.
- This approach to weld testing appears to be applicable to magnetic steel pipe diameters from less than 5 mm (2") up to flat plate.
- The phased array system was capable of focusing the SH wave beam to a focal spot of approximately 2 mm (.080") by 2 mm (.080") in magnetic steels.
- The system was capable of electronically sweeping the focal spot and determining the through wall height of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040").
- The system was capable of determining the circumferential length of lack of fusion defects in magnetic steel welds to within approximately +/- 1 mm (.040") by moving the focused beam testhead along the weld and monitoring the defect signal as a function of position.
- The path length to the defects in magnetic steel welds could be determined to within approximately +/- 0.5 mm (.020") from time of flight measurements.
- The system was capable of detecting lack of root penetration defects in magnetic steel welds with excellent signal to background noise, due to the absence of mode conversion with the SH wave mode.
- Lack of fusion at the weld cap was readily detected with a surface skimming (90°) SH wave in a magnetic steel weld using the phased array EMAT system.
- The use of a phased array system and shear horizontal waves allowed innovative methods of tandem (separate transmitter receiver locations) operation.
- Weld splatter must be removed from the inspection area around the weld in order

to prevent excessive liftoff of the sensor and to prevent possibly damaging the EMAT coil.

- Modifications to the system to improve the electronic signal-to-noise ratio and make the system field worthy will have to be incorporated in order for the system to be used in routine inspections of magnetic steel welds.

- A rapid drop in angle beam EMAT sensitivity with frequency for nonmagnetic high-resistivity metals makes it impractical to operate at frequencies high enough to provide adequate defect through wall height resolution for inspecting piping welds in these metals.

- At relatively low frequencies (1 MHz and less), EMATs are several times less sensitive for nonmagnetic high-resistivity metals such as stainless steel, Inconel, and nickel copper than for magnetic or low-resistivity metals such as magnetic steels and aluminum.

5.5 RECOMMENDATIONS

Positive results for the evaluation of phased array EMATs to inspect welds in magnetic steel piping warrant the further development of the technology and implementation of a shipyard system for inspecting these welds. The system would be of primary benefit in replacing manual ultrasonic testing of these welds, providing improved inspections at much faster scan rates, with computer documented results. The fully developed system would allow rapid reconfiguration for welds in piping of different diameter, thickness, and weld configuration. The next phase of development for this system should include the following tasks:

- Generate a specification covering pipe diameters, wall thickness, weld configurations, and types of defects to be used in defining the system. Also included in this specification should be scan rate, operating environment, calibration, and documentation requirements.

- Identify modifications to the system needed to be able to meet the specifications. These are expected to include the modification of the EMAT sensor and remote electronics to improve the sensitivity of the system and to field harden the system. In addition, software which would integrate control of the system with data processing and provide a user interface to take full advantage of the system's capabilities will likely be required.

- Incorporate the required modifications into the system and perform laboratory testing to verify the operation of the system.
- Transport the system to a shipyard and perform field trial inspections on actual piping welds.
- The results of the field trials would be used to guide the development of a commercial inspection unit.

The results for the evaluation of inspection of non-magnetic high-resistivity metals such as stainless steel, Inconel, and nickel copper alloys with phased array EMATs, indicate that these EMATs are not capable for providing defect through wall height measurement with adequate resolution to be useful in most shipyard piping weld inspections. If special circumstances are identified where conventional RT or UT are deemed inappropriate, and high through wall resolution is not required, then phased array EMAT inspections for these materials could be considered.

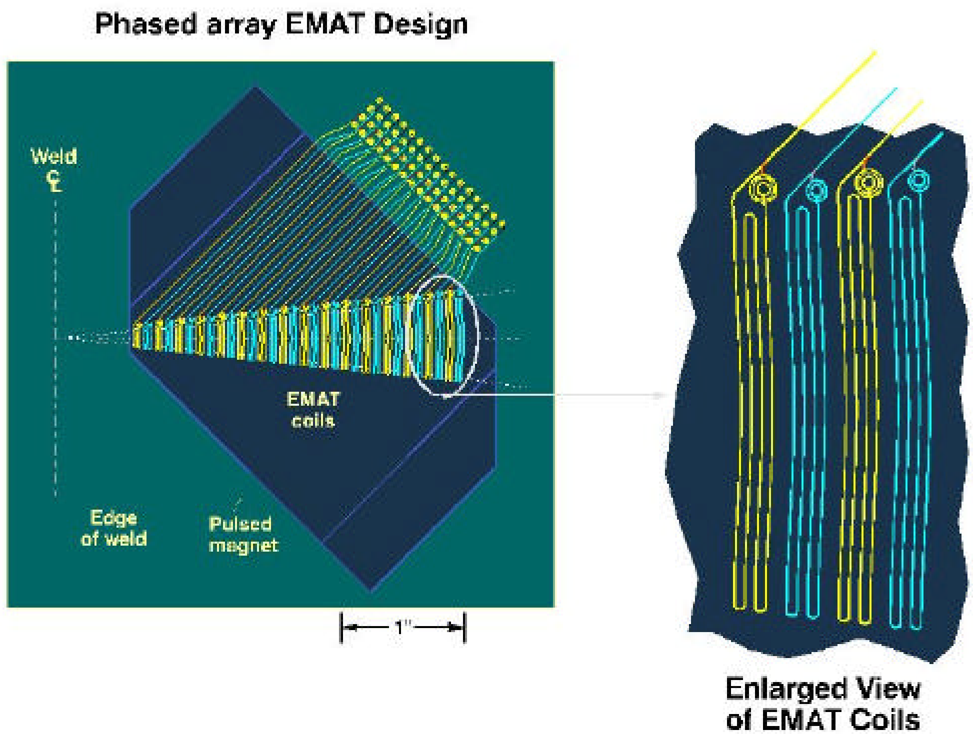

Figure 1 - Phased Array EMAT Probe for Magnetic Steel

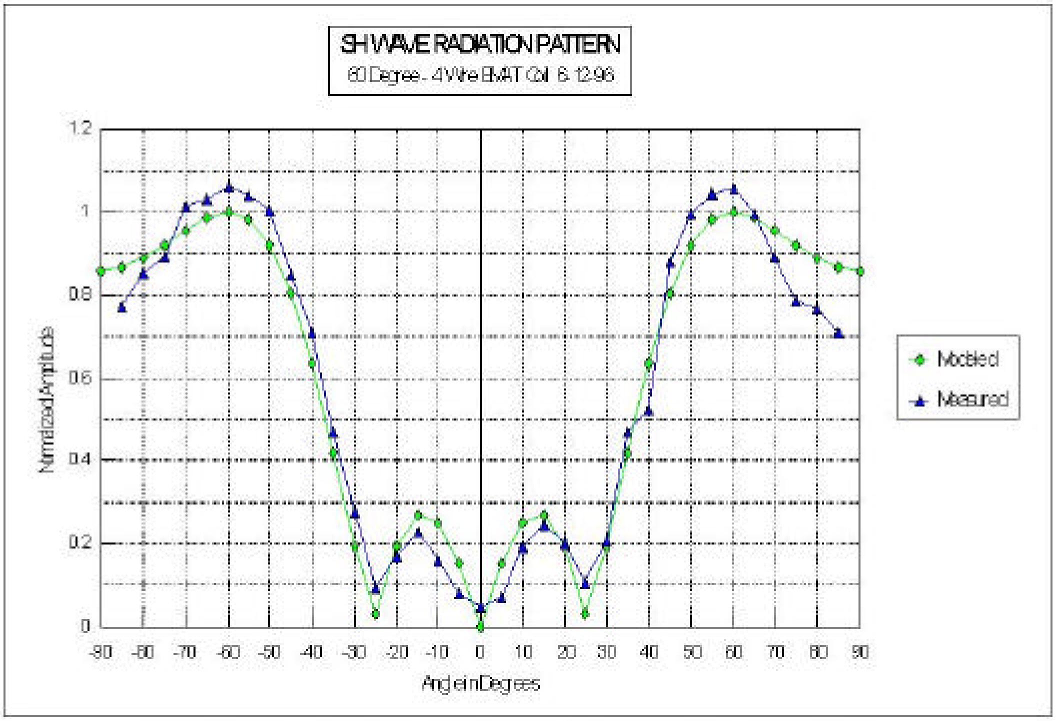

Figure 2 - Single Element Radiation Pattern

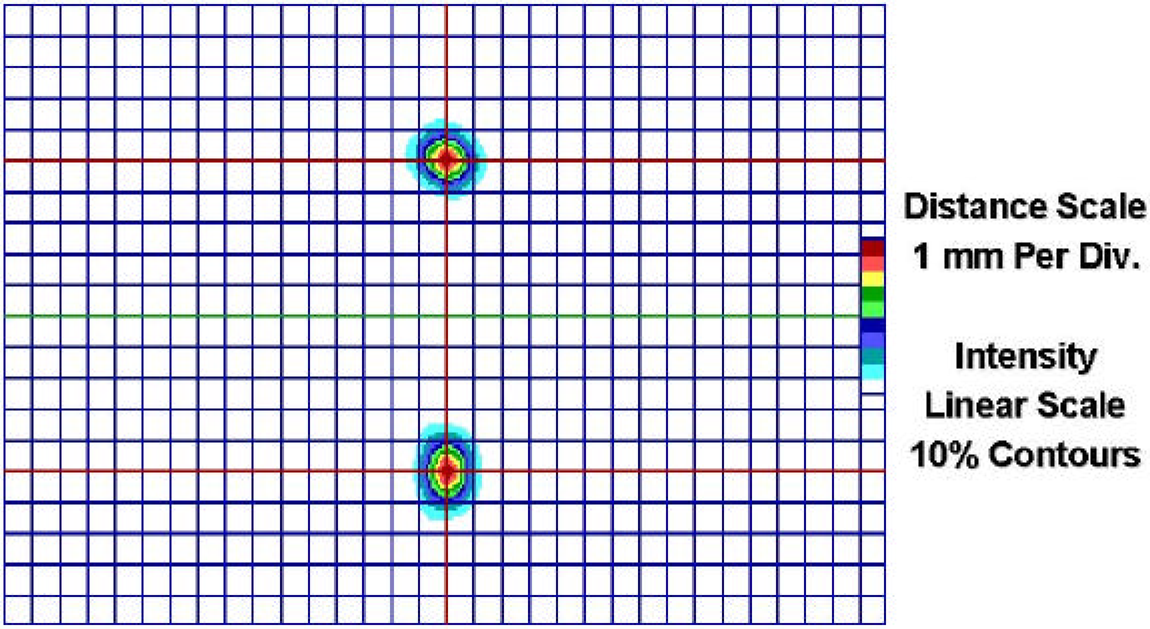

Figure 3 - Simulated Wave Packet Intensity at Focal Point (-.72", 45º Beam Angle)

Figure 4 - Phased Array SH Wave EMAT System

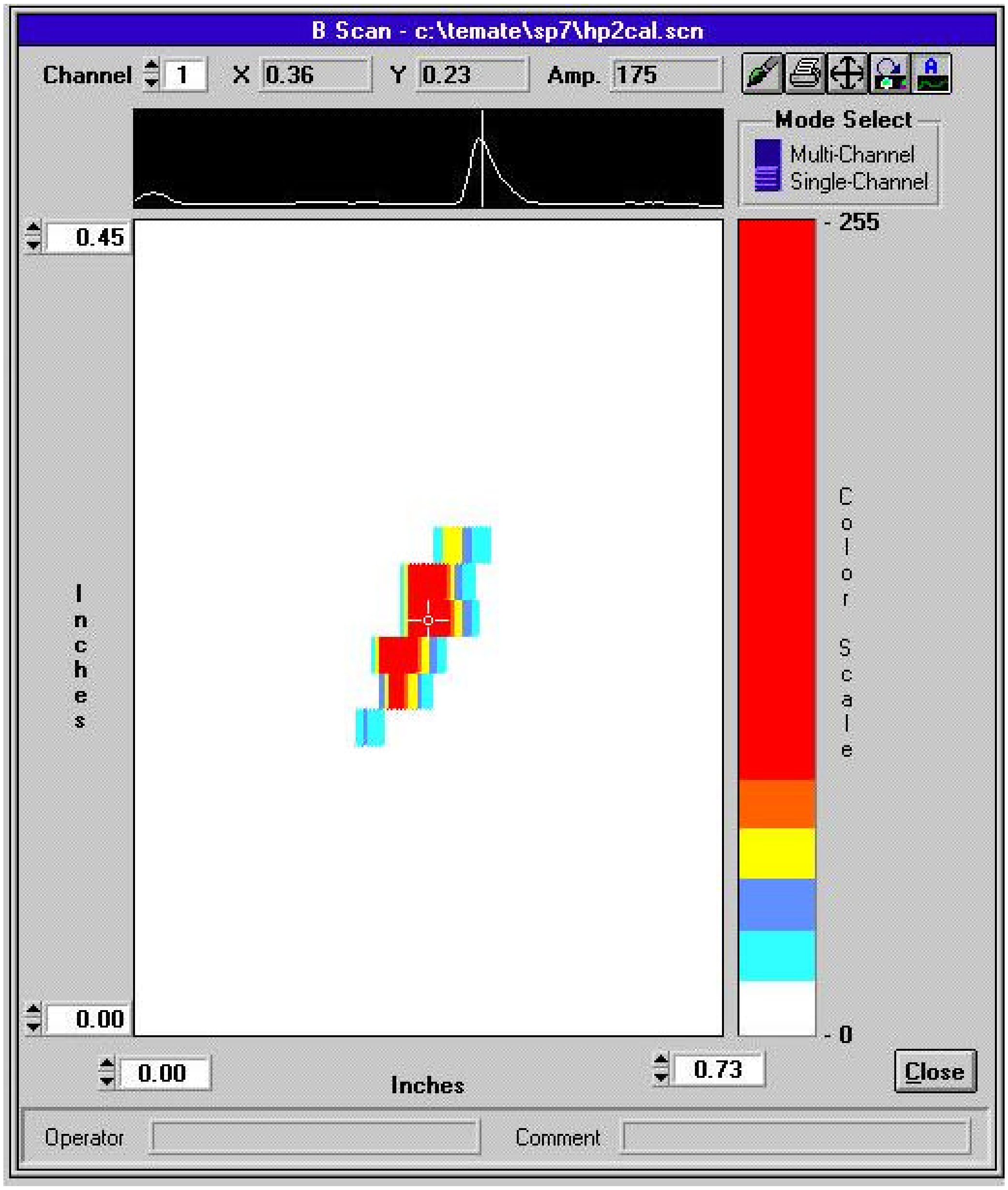

Figure 5-5 B-S can of 3 mm Flat Bottomed Hole

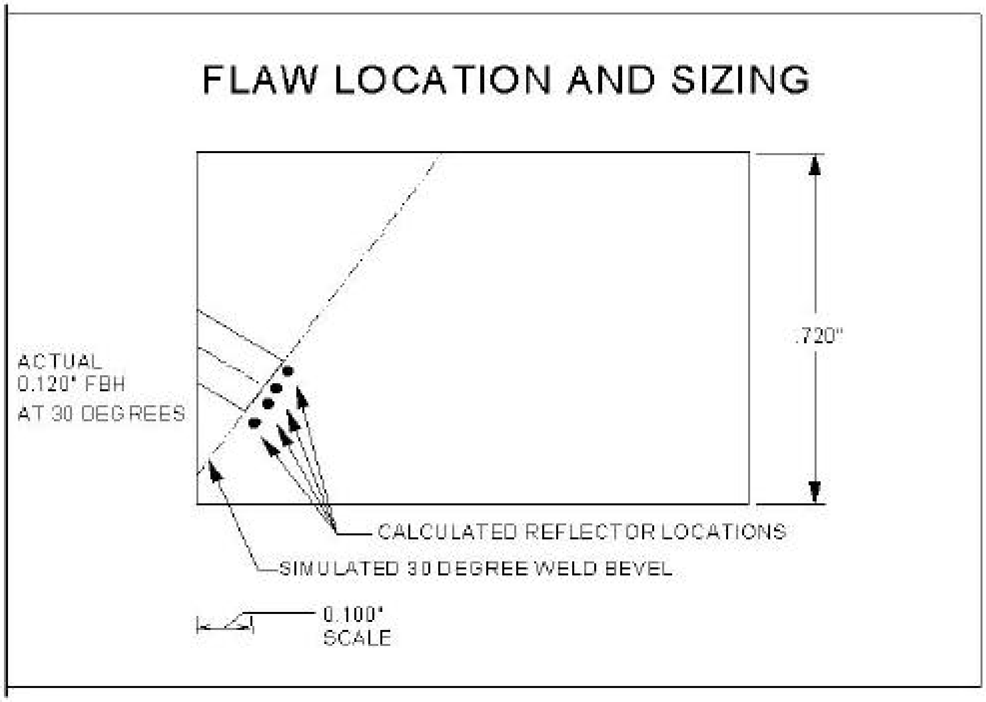

Figure 6 - 3 mm Flat Bottomed Hole Indication

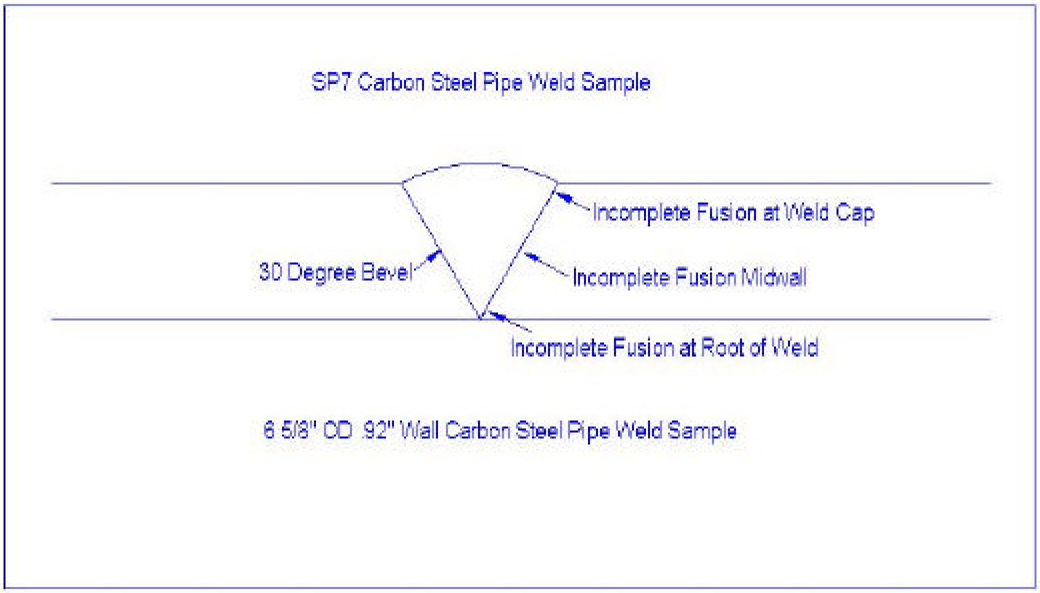

Figure 7 - 6.5" OD .91" Wall Carbon Steel Weld Sample

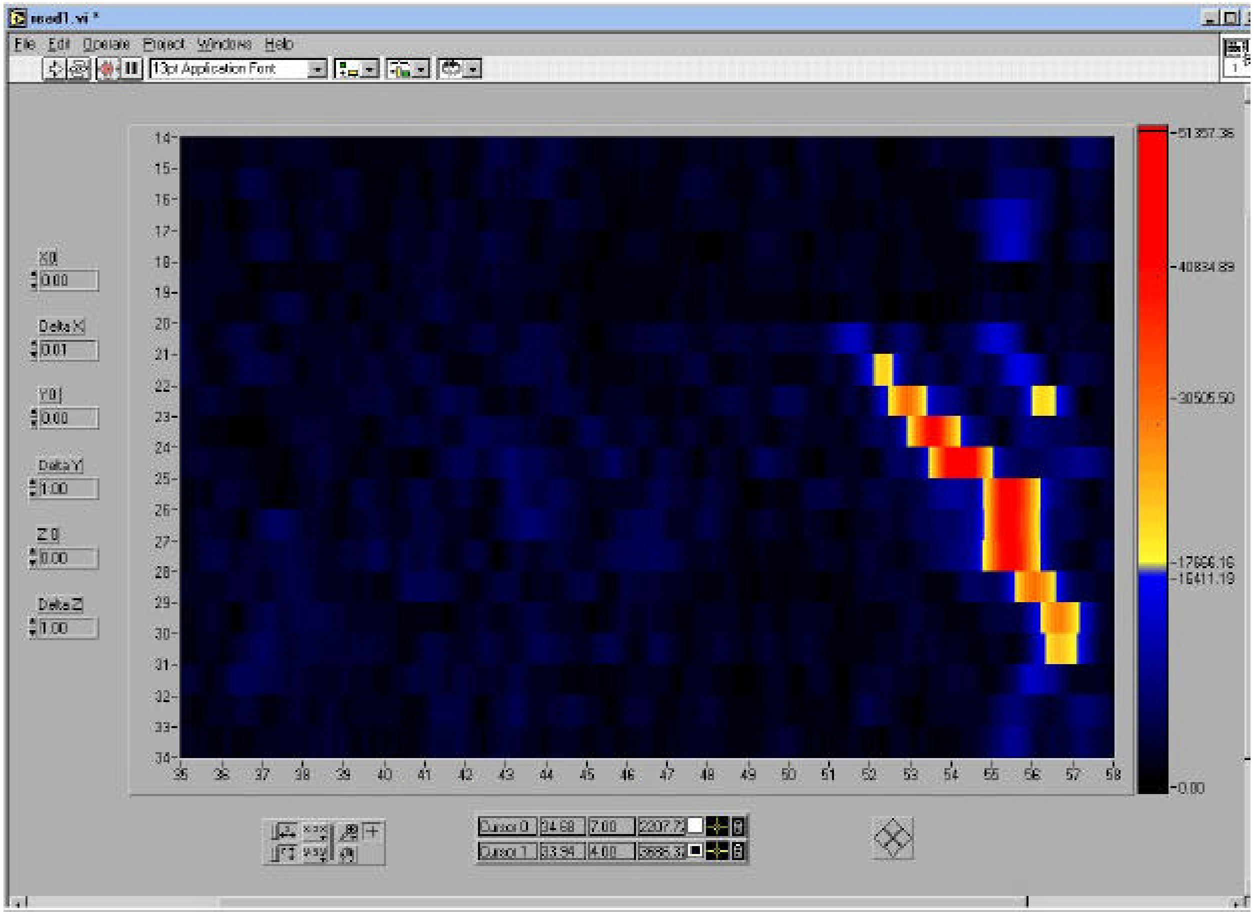

Figure 5-8 Lack of Fusion Defect Indication

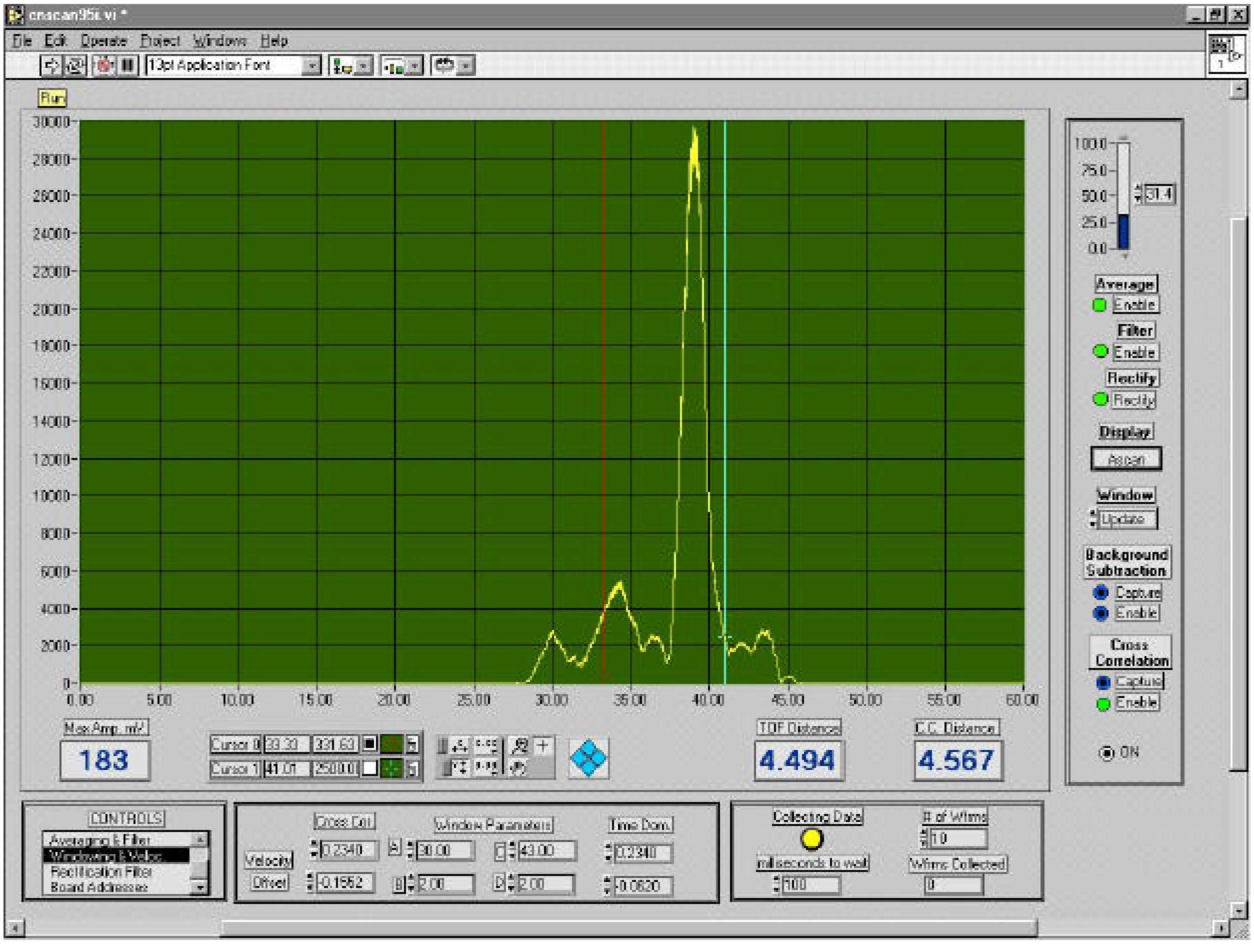

Figure 5-9 A-scan Showing Reflection From Lack of Root Penetration Defect

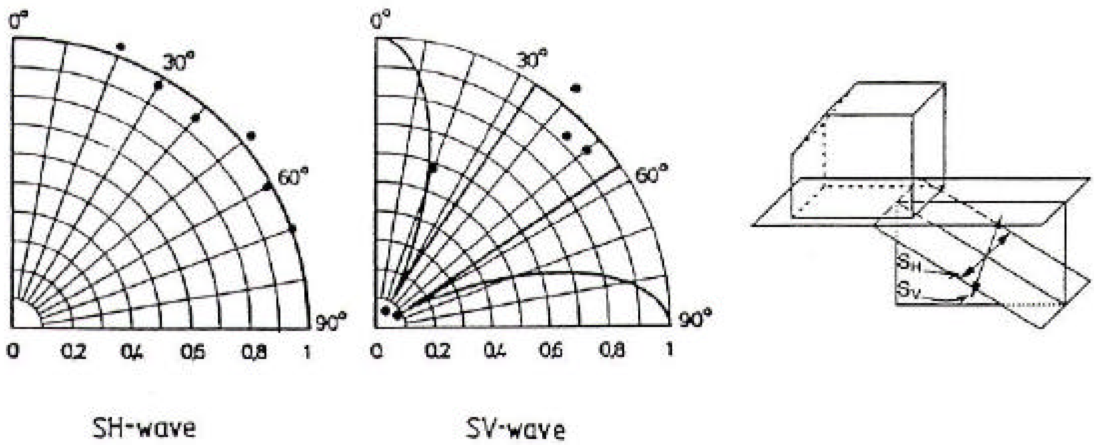

Figure 10 - Comparison of Corner Reflector Response Vs. Angle of Incidence for SH and SV Waves

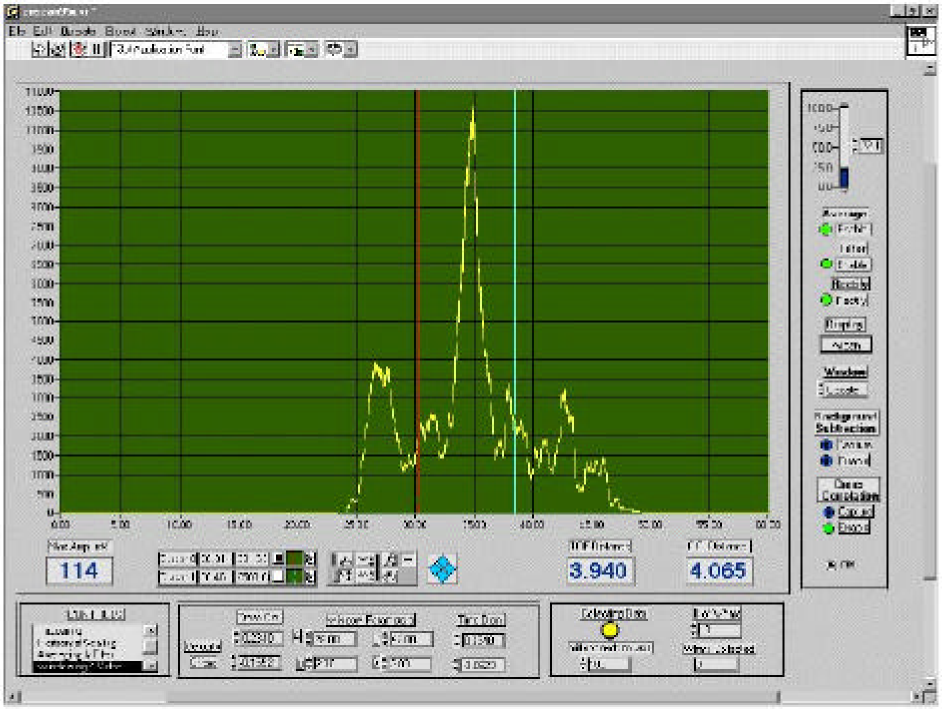

Figure 11 - A-scan Showing Reflection From Lack of Fusion Defect at Weld Cap

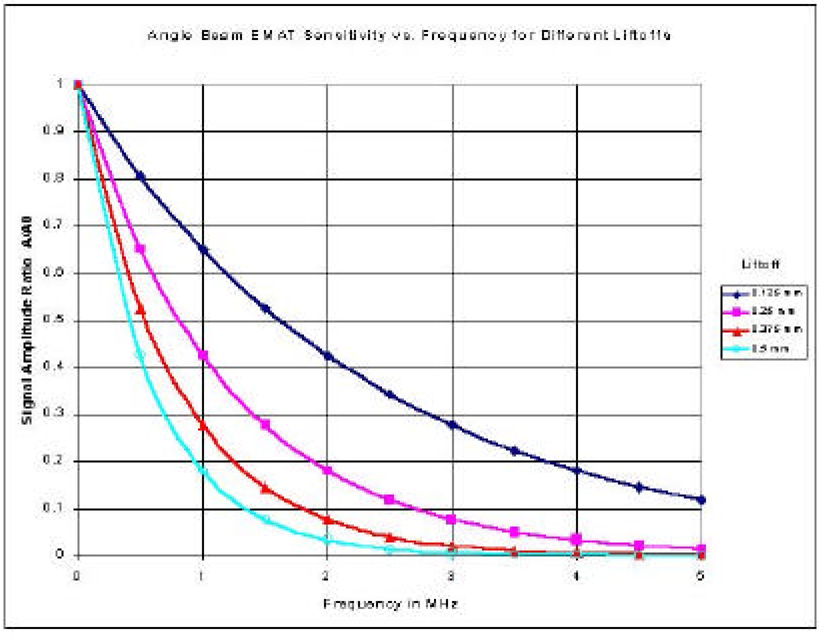

Figure 12 - Graph Showing Angle Beam EMAT Sensitivity Dependence on Frequency and Liftoff

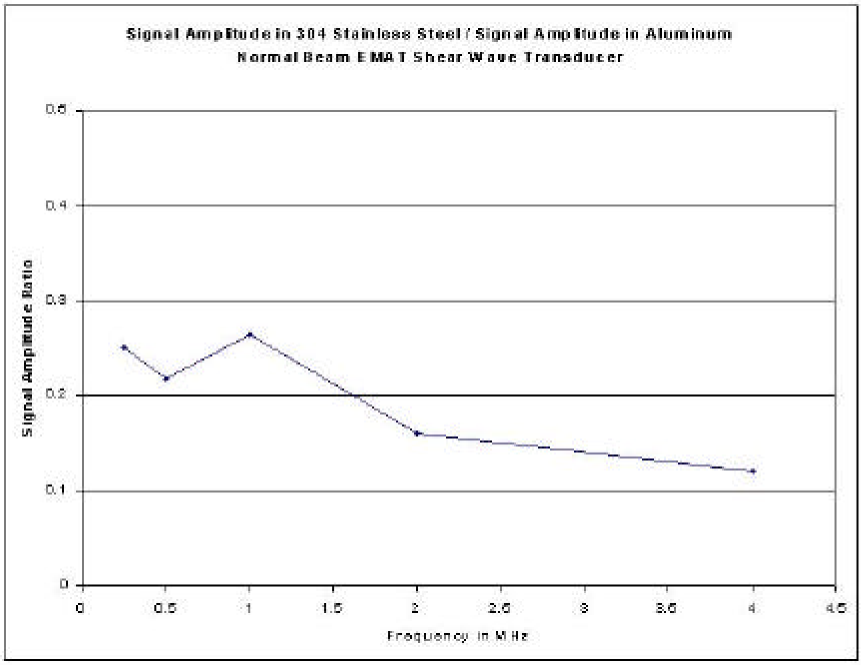

Figure 13 - Ratio of Signal Amplitude in Stainless Steel to Signal Amplitude in Aluminum Vs. Frequency

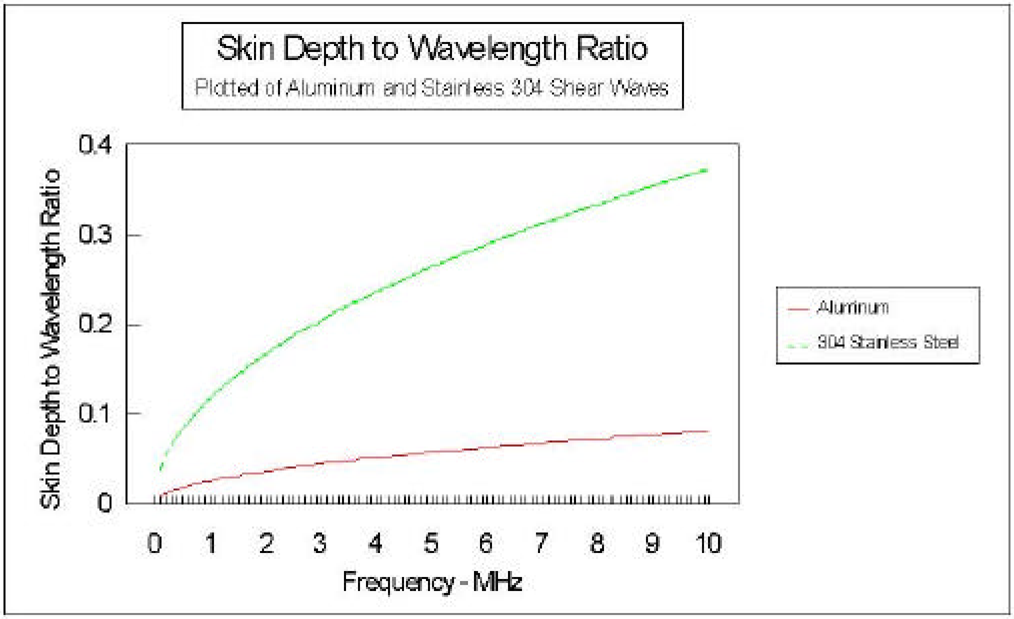

Figure 14 - Ratio of Signal Amplitude in Stainless Steel to Signal Amplitude in Aluminum Vs. Frequency

6.0 EMAT INSTRUMENTATION DESIGN FOR MAXIMUM PORTABILITY

DEVELOPMENT OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS (EMATS) FOR SURFACE/VOLUMETRIC INSPECTION OF WELDS

- FINAL SUMMARY REPORT -

EMAT INSTRUMENTATION DESIGN FOR MAXIMUM PORTABILITY

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January 17, 2000

PREPARED FOR

HALTER MARINE GROUP, INC.
GULFPORT, MS
AND
NAVAL SURFACE WARFARE CENTER

HMGI PURCHASE ORDER NO. 2228
PROJECT NO. 7-96-1
MTI CONTRACT NO. CRD - 1355

6.1 SUMMARY

This project involves the development of EMAT techniques for both surface and volumetric weld inspection, specifically for shipyard use. It is a continuation of earlier programs sponsored by the SP-7 Welding Panel of the National Shipbuilding Research Program and General Dynamics - Electric Boat Division (EB) through Knolls Atomic Power Lab (KAPL). This report documents the results of NSRP project 7-96-1 Phase 2, Tasks 3 "Establish EMAT Instrumentation Design for Maximum Portability". The current work involves the development of EMAT instrumentation designs for improved portability.

The high cost, large size, and complexity of current EMAT instrumentation has been a limiting factor in the application of EMATs for field use. Most of the EMAT systems that are commercially available today are large systems developed for stationary installation in factories. Until recently the components needed to implement small, lightweight, low-cost EMAT systems were not readily available. Through a series of developments at McDermott Technology, the basic components for portable low-cost EMAT systems are now available. A top-level design of a portable EMAT system based on these developments has been conducted for application in shipyard inspections.

The results of this investigation into the design of EMAT instrumentation for portable applications in the shipyard indicate that it is possible today to build small lightweight portable EMAT instruments. This conceptual design, based on a ruggedized laptop PC, avoids the high development costs of an embedded processor system, while providing a full-featured portable instrument for field use. In applications where permanent magnet based EMAT probes are used, the estimated weight of the EMAT instrumentation is 13 to 14 lbs. when using AC power, and 17 to 18 lbs. using a battery pack. The EMAT electronics module and battery pack module would match the footprint of the laptop PC in area, and be approximately 1" high each. The EMAT electronics module would attach to the bottom of the laptop PC, and the battery pack to the bottom of the EMAT electronics module. For operating pulsed magnet based EMAT probes, a magnet pulser module would attach to the bottom of the EMAT electronics module. This module would match the laptop footprint in area and is estimated to be less than 4" in depth and would weigh 6 to 8 lbs. In this design concept a visor-mounted display could be used for hands-free single man operation.

The areas where such systems would have the greatest impact are areas where the unique capabilities of EMATs provide advantages for non-destructive testing. Many of these EMAT inspection techniques have already been proven, both in the laboratory and in the field, and are awaiting the development of low-cost portable instrumentation in order to be commercially viable.

The areas of greatest impact for this development are expected to be:

- High-speed manual scanning applications for thickness gauging and flaw detection which take advantage of the elimination of couplant using EMATs.
- Semiautomatic scanners and crawlers for thickness gauging and flaw detection applications, taking advantage of the ease of automation by eliminating the use of couplant using EMATs.
- Applications that take advantage of EMATs unique ability to utilize shear horizontal (SH) waves, Lamb waves, and Raleigh waves to perform inspections in a practical manner.
- Inspection applications for thickness gauging and flaw detection at elevated temperatures.
- Applications that take advantage of EMATs ability to electronically sweep the inspection beam in angle, such as the detection of defects oriented at random angles.

6.2 BACKGROUND

A comprehensive introduction and background for the project is given at the beginning of this final report.

6.3 EMAT INSTRUMENT DESIGN FOR MAXIMUM PORTABILITY

EMATs are a non-contact method of generating and receiving ultrasound in conductive and magnetic materials. Typically a wire coil is used to set up dynamic eddy currents and magnetic fields in the surface of the material. A static or quasi-static magnetic field is also set up in the surface of the material using permanent magnets, electromagnets, or pulsed electromagnets. Lorentz and/or magnetostrictive forces are generated in the surface of the material due to the interaction of the dynamic fields and the static fields. These dynamic surface forces generate ultrasonic waves in the material. A reciprocal process allows ultrasonic waves striking the surface to be detected using these same transducers. Using different combinations of magnet and coil configurations, a wide variety of wave types and beam characteristics can be achieved. Being non-contact, EMATs are useful in automated ultrasonic testing (UT) systems. They can also be used for inspecting materials at elevated temperatures and have been used at temperatures in excess of 2000° F in some applications. Since ultrasound is generated and received directly in the surface of the part being inspected, wedges or ultrasonic delay lines are not required, and the errors produced by time delay variations in these components of conventional ultrasonic testing are eliminated. Typically EMAT coils are fabricated using photo-etching techniques resulting in nearly identical characteristics from transducer to transducer.

The high cost, large size, and complexity of EMAT instrumentation has been a limiting factor in the application of EMATs for widespread field use. Figure 6-1 shows a typical present day EMAT laboratory system used to perform surface inspection of boiler tubes. A lunchbox-style PC, EMAT electronics, and a magnet pulser are interconnected to provide the required functions. Moving from one inspection area to another requires disconnecting the equipment and interconnecting cables, transporting the individual components to the new location, and reconnecting the instruments together. The total weight of these components is approximately 80 lbs.

Details of a hardened EMAT sensor conceptual design for field use were presented in the final report for phase 1 of this project. This probe uses permanent magnets to provide the required magnetic field. This design provides for improvements in ease of use, maintenance, and durability. This probe is primarily intended for surface examinations.

Most of the EMAT systems that are commercially available today are large systems developed for stationary installation in factories. Until recently the components needed to implement small, lightweight, low-cost EMAT systems were not readily available. Through a series of developments at McDermott Technology, the basic components for portable low-cost EMAT systems are now available. A top-level design of a portable EMAT system based on these developments has been conducted for application in shipyard inspections. The development of low-cost portable EMAT instrumentation could have widespread use for shipyard inspections and throughout industrial NDE. The areas where such systems would have the greatest impact are areas where the unique capabilities of EMATs provide advantages for non-destructive testing. Many of these EMAT inspection techniques have already been proven, both in the laboratory and in the field. Many of these techniques are awaiting the development of low-cost portable instrumentation in order to be commercially viable. These areas of greatest impact for this development are expected to be:

- High-speed manual scanning applications for thickness gauging and flaw detection which take advantage of the elimination of couplant using EMATs.

- Semiautomatic scanners and crawlers for thickness gauging and flaw detection applications, taking advantage of the ease of automation by eliminating the use of couplant using EMATs.

- Applications that take advantage of EMATs unique ability to utilize shear horizontal (SH) waves, Lamb waves, and Raleigh waves to perform inspections in a practical manner.

- Inspection applications for thickness gauging and flaw detection at elevated temperatures.

- Applications that take advantage of EMATs ability to electronically sweep the inspection beam in angle, such as the detection of defects oriented at random angles.

The results of earlier tasks of this project indicate that the use of EMATs to perform surface examinations of both welds and component surfaces is closest to being implemented in actual online shipyard testing to replace penetrant testing. The portable EMAT instrumentation design considered in this report specifically addresses the EMAT instrumentation requirements for this inspection as well as others. This design has also benefited from recent experience in using EMAT based testing for the surface examination of electric utility boiler tubes for longitudinal and circumferential cracking.

Field experience with present day EMAT instrumentation has produced the following observations for improved portable EMAT instrumentation:

- The main instrument should be comprised of a single integrated unit with a single connection for the EMAT probe cable.
- Weight and size of the main instrument are dictated by that which can be easily transported by one man in moving from one inspection site to another. Operator carried operation is not needed or even desirable in most applications, if a reasonably long connecting cable for the probe head and display can be used.
- A visor-mounted display will be needed for single operator inspections.
- A primary goal is to minimize the time it takes to move from one inspection site to another and resume testing.
- Battery operation would be useful although at most sites AC power is available.
- In some cases EMATs can be scanned at up to 1 foot per second using a two-man team. One operator concentrates on scanning the probe properly while the other interprets and records the inspection results. The operators can switch off from time to time to prevent operator fatigue and a visor-mounted display is not required. The increased scan rates offset the additional labor costs of having two operators.
- The instrument must be very rugged and reliable.

A conceptual design for the system has been developed and is shown in Figure 6-2. Figure 6-3 shows a block diagram of the system. The design is based around the use of a ruggedized laptop PC to provide the functions of hardware control, timing control, received signal waveform acquisition, signal processing, data display, data archiving, and user interface (Figure 3). The use of a standard PC to provide these functions reduces the cost of the system and allows the system to be easily upgraded with new developments in PC technology. Typical ruggedized laptop PCs weigh 10-12 lbs. A key component in being able to use a laptop computer is the availability of data acquisition and I/O boards in PCMCIA formats. McDermott Technology recently substituted a laptop PC and a PCMCIA digitizer board for a lunchbox-style computer with an ISA style digitizer card (shown in Figure 6-1) to perform EMAT surface inspections for boiler tubes in an electric utility boiler. The laptop PC performed well in this application.

6.3.1 EMAT Electronics Module

A flat rectangular module would attach to the bottom of the laptop PC and contain the EMAT pulser board, receiver board, and power supply. For applications using permanent magnet EMAT probes and AC operation, this module attached to the laptop computer is all that would be needed for the main instrument. This module would provide several functions. A programmable high-powered radio frequency (RF) toneburst would be generated for transmitting EMAT signals. Low noise programmable gain circuitry would be used to condition the received EMAT signal before sending it on the laptop's waveform digitizer card. Circuitry for interfacing to an odometer wheel and operator controls would also be included.

Existing printed board designs for the EMAT pulser board, receiver board, odometer circuitry, and operator controls would be consolidated and miniaturized using surface mount device technology and other circuit miniaturization techniques. It is expected that the resulting board would be less than 6" x 6" in area and less than 3/4" tall. Preliminary design reviews with printed circuit board manufacturers indicate that the required miniaturization could readily be accomplished.

The component that primarily determines the size and weight of this module is the power supply. A custom DC/DC converter power supply would be specified and purchased to minimize size and weight. The primary factor in determining the size and weight of the power supply is the power required. A 25-watt power supply would provide ample power for the EMAT pulser board and other EMAT electronics. A typical 25-watt DC/DC converter module is approximately 2.5" wide, 2.5" deep, 0.5" tall, and weighs less than 1 lb. In total the module would match the laptop footprint in area and would be 1" to 1.5" tall. This module is expected to weigh 4-5 lbs. An external transformer and power cord would provide power for battery charging and operation from an AC power source, similar to most

laptops PCs. The total weight for EMAT electronics module and ruggedized laptop PC is expected to be 14-15 lbs.

6.3.2 Battery Operation

Battery operation for the EMAT circuitry would be supplied by attaching a second rectangular module under the EMAT electronics module. It is anticipated that nickel metal hydride batteries would be used. Figure 6- 4 is a graph of the required battery weight to achieve a desired operating time for duty factors of 25, 50, and 100%. In these calculations the use of nickel hydride batteries and 75% power conversion efficiency is assumed. The duty factor is the percent of time the unit is actually operating divided by the total elapsed time. The power consumption of the unit in a standby mode is assumed to be negligible. In portable inspection use the duty factor is typically much less than 100%, with 25% being more typical. The EMAT pulser consumes almost all the required power. The EMAT pulser developed by MTI is very efficient and draws negligible power when not pulsing. A key to maximizing the operating time for a given battery size is to only pulse the EMAT when needed to perform the inspection. The graph shows that a 3 lbs. battery pack would last 8 hours at a 25% duty factor, 4 hours at 50%, and 2 hours at 100%. This battery pack could easily be housed in a module that matches the footprint of a laptop PC and would be less than 1" high. Additional battery pack modules could be used as needed to prevent having to wait for recharging. With a 3 lbs. battery pack the total additional weight that the EMAT electronics would add to the weight of the laptop PC is estimated to be 8 to 9 lbs. The total weight of the EMAT electronics with the battery pack and a typical laptop PC would be approximately 18 to 19 lbs. for operation with a permanent magnet EMAT probe.

6.3.3 Magnet Pulser

Providing the required magnetic field with a pulsed magnet is very useful for EMAT inspection of magnetic materials. The use of a pulsed magnet eliminates the magnetic attraction between the EMAT probe and the component. The elimination of the attractive force makes it much easier to scan the component, and to remove the probe from the component when scanning has been completed. For portable applications requiring pulsed magnets a lightweight magnet pulser module would be developed that would attach to the bottom of the EMAT electronics module. It is expected that the magnet pulser could only be used with AC power operation.

A high-energy pulse is used to drive the pulsed magnet. A typical application will require peak pulse powers of 10 kW. Average power requirements for operation of the pulsed magnet range from 50 watts to 1 kW depending on the application. For the most part, it is not practical to supply these power requirements using a lightweight battery pack. An AC power supply for the magnet pulser can be formed by using small lightweight power modules commercially available today. A 200-watt AC/DC power module is available today that is only 4.6" long, 2.5" wide, and less than 1" tall. This power module weighs 0.5 lbs. By combining two or more of these modules together higher powers can be obtained.

The components used in the magnet pulser circuitry can be readily miniaturized. Although the peak power ratings are quite high, the average power ratings are low enough to facilitate the development of a small lightweight module to provide the required magnet drive pulses. Transistor switching generates the pulses and the power dissipated in the transistors is low, typically less than 10 watts. This switching can be accomplished using relatively small power transistors. A capacitor bank is used to supply the large pulsed currents and even out the current draw from the power supply. The capacitor bank can be the largest component in the magnet pulser circuitry. Fortunately the capacitor bank can be formed by paralleling several smaller capacitors together, allowing a great deal of flexibility in packaging the needed capacitance. It is anticipated that the magnet pulser module would be two layered, with power supplies on the lower layer and the pulser circuitry on the upper layer. The completed magnet pulser module is expected to match the footprint of a laptop PC in area and be less than 4" in depth. This module is expected to weigh 6-8 lbs. The total weight of the magnet pulser module, EMAT electronics module, and ruggedized laptop PC is estimated to be 20 to 23 lbs.

6.3.4 Operator Display

For single operator inspections using the miniaturized EMAT system, a remote display is needed that allows the operator to view the computer display, and leaves both hands free to manipulate the probe. Several methods for providing a hands-free display have been investigated at MTI. One method was the use of a flat panel display with straps around the operator's neck and waist to hold it out for viewing by looking down at the display. A second method was the use of a heads-up display where a computer display image is projected onto the operator’s field of vision and appears as a semi-transparent foreground to whatever the operator is looking at. Finally the use of a head-mounted display was also investigated. We have discussed the different displays with NDE inspectors who have used them in the field.

The flat panel display has been found to be somewhat cumbersome and difficult to use. The operator must look nearly straight down to view the display, losing sight of the probe and component being inspected, even in his peripheral vision. Heads-up displays cause some obstruction of the operator's view of the probe and component being scanned, while projecting an image of the computer display that is of poorer quality than viewing an actual computer display. The head-mounted display can provide a good quality display and a relatively unobstructed view of the probe and component. Figure 6-5 shows a head-mounted display. This unit is the PT-01 model display available from Optics 1, Inc. in Westlake, California. In use the operator adjusts the position of the display to be slightly above normal straight-on viewing. The probe and component are viewed by looking straight ahead or down and the display is viewed by looking up slightly. The display remains in the operator's peripheral vision while viewing the probe and vice versa. The display graphics software must be tailored to make the most effective use of this display. This unit is also available in a hardhat-mounted version and audio output is available, which can be used to prompt the operator when the software detects that some preset conditions have been met.

6.3.5 Probe Mounted Preamplifier and Matching Network

In the majority of EMAT applications, a low noise preamplifier and transmitter-matching network is mounted in the EMAT test head, as close as possible to the EMAT coils. This maximizes the signal to noise ratio and allows operation with long cables between the EMAT probe and the main EMAT instrumentation. The preamplifier is used to amplify the small signals detected by the receiver EMAT coil and send the amplified signal down the long connecting cable back to the main EMAT instrument. A current preamplifier design occupies 1” by 1” by 0.5” deep and is shown in Figure 6-6. This circuit could be miniaturized even further, as small as 0.5” by 0.5” by 0.25” deep using surface mount devices if needed. The transmitter matching network is used to minimize loss in transmit pulse power in the long connecting cable and maximize the power transferred to the EMAT coil. The size of the matching network is set by the size of the power handling components that are used. By careful design these sizes can be minimized. The size of these components is very application specific, but can be as small as 1” by 1” by 0.5” deep.

6.4 CONCLUSIONS

The results of this investigation into the design of EMAT instrumentation for portable applications in the shipyard indicate that it is possible today to build small, lightweight, portable EMAT instruments. This conceptual design based on a ruggedized laptop PC, avoids the high development costs of an embedded processor system, while providing a full-featured portable instrument for field use. In applications where permanent magnet based EMAT probes are used, the estimated weight of the EMAT instrumentation is 14 to 15 lbs. when using AC power, and 18 to 19 lbs. using a battery pack. The EMAT electronics module and battery pack module would match the footprint of the laptop PC in area and be approximately 1” high each. The EMAT electronics module would attach to the bottom of the laptop PC, and the battery pack to the bottom of the EMAT electronics module. For operating pulsed magnet based EMAT probes, a magnet pulser module would attach to the bottom of the EMAT electronics module. This module would match the laptop footprint in area and is estimated to be less than 4” in depth and weigh 6 to 8 lbs.

In this design concept a visor-mounted display could be used for hands-free single man operation.

The areas where such systems would have the greatest impact are areas where the unique capabilities of EMATs provide advantages for non-destructive testing. Many of these EMAT inspection techniques have already been proven, both in the laboratory and in the field and are awaiting the development of low-cost portable instrumentation in order to be commercially viable.

These areas of greatest impact for this development are expected to be:

- High-speed manual scanning applications for thickness gauging and flaw detection which take advantage of the elimination of couplant using EMATs.

- Semiautomatic scanners and crawlers for thickness gauging and flaw detection applications, taking advantage of the ease of automation by eliminating the use of couplant using EMATs.

- Applications that take advantage of EMATs unique ability to utilize shear horizontal (SH) waves, Lamb waves, and Raleigh waves to perform inspections in a practical manner.

- Inspection applications for thickness gauging and flaw detection at elevated temperatures.

- Applications that take advantage of EMATs ability to electronically sweep the inspection beam in angle, such as the detection of defects oriented at random angles.

6.5 RECOMMENDATIONS

Positive results for the evaluation of a conceptual design of a small lightweight portable EMAT instrument for use in shipyard inspections warrant the further development and implementation of the instrument. The development of low-cost portable EMAT instrumentation could have widespread use for shipyard inspections and throughout industrial NDE. It is recommended that with the results of this conceptual design in mind, the most promising EMAT based shipyard inspections be identified, and detailed specifications for a portable EMAT instrument developed. Based on these specifications a portable EMAT instrument should be fabricated for use in shipyard testing trials. Improvements based on the results of the shipyard trials could then be incorporated in the production of commercial units.

Figure 6-1 Present Day Laboratory EMAT System Used For Surface Inspection of Boiler Tubes.

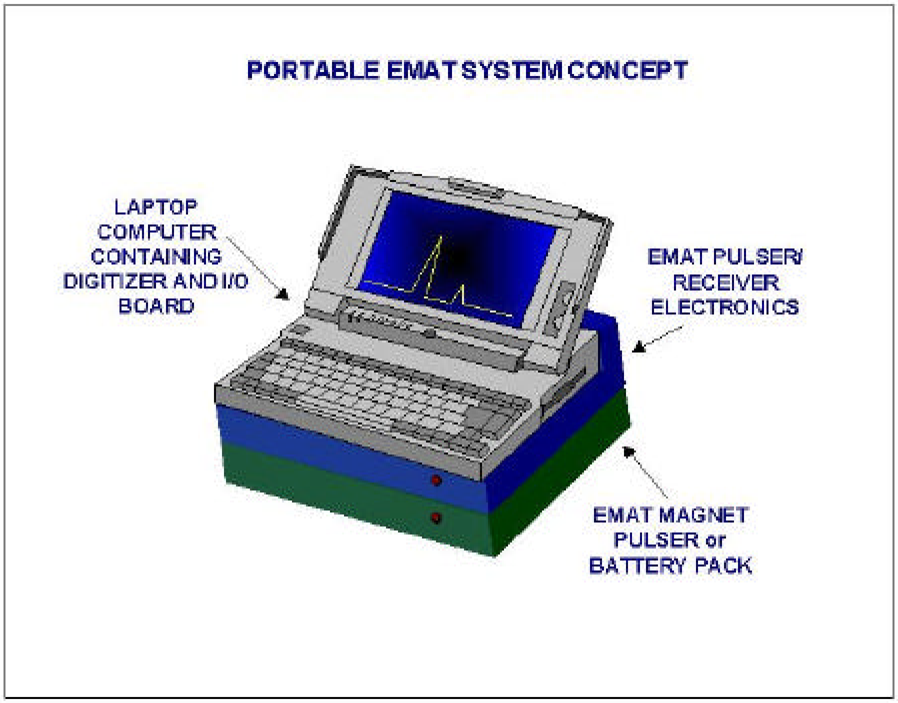

Figure 6-2 Portable EMAT System Concept For Shipyard Inspections

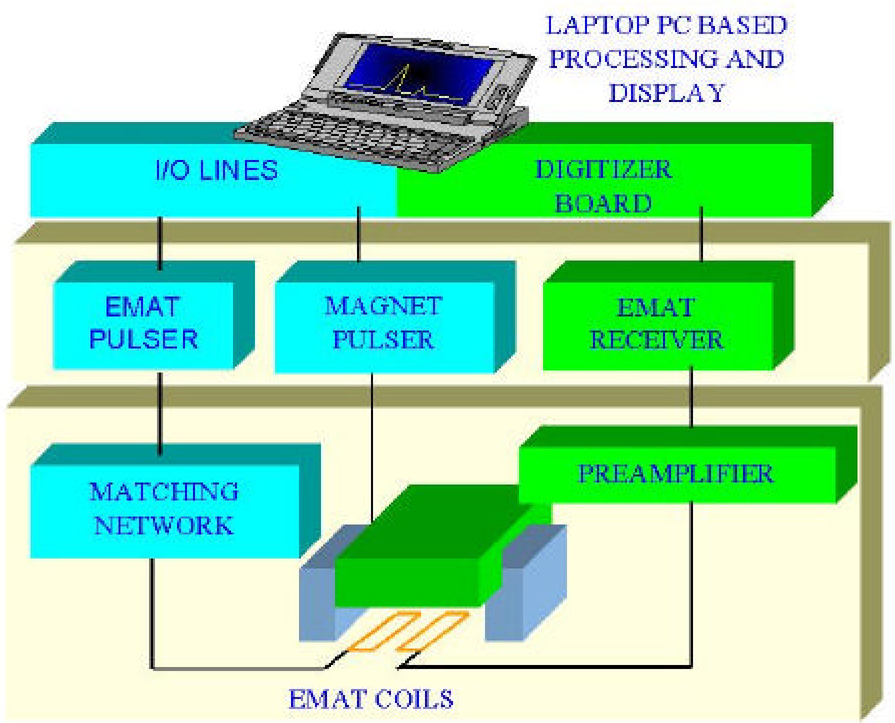

Figure 6-3 Portable EMAT System Block Diagram

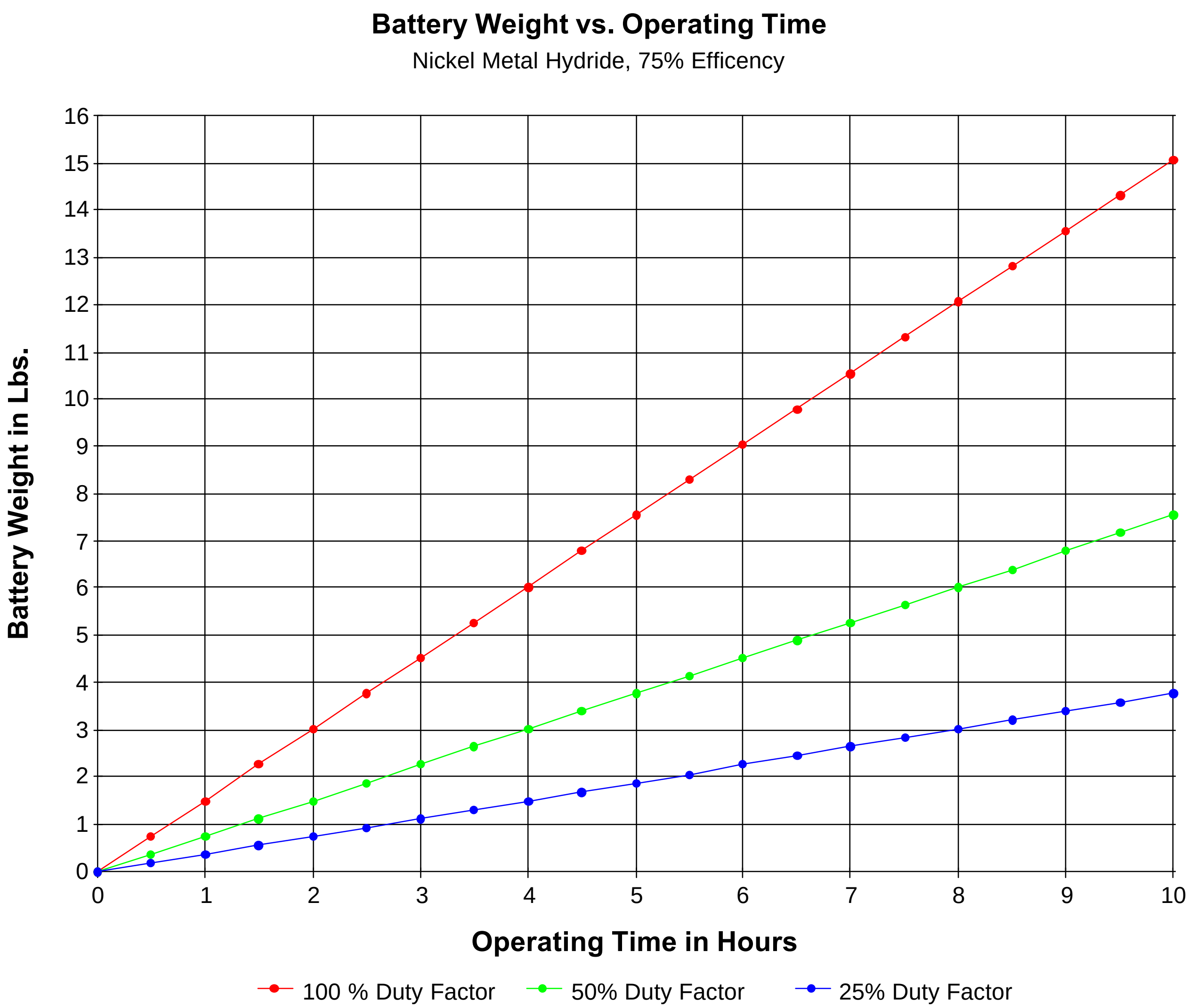

Figure 6-4 Portable EMAT System Graph of Battery Weight vs. Operation Time

Figure 6- 5 - Portable EMAT System PT-01 Hardhat Mounted Computer Display

7.0 CONCLUSIONS

ElectroMagnetic Acoustic Transducers (EMATs) can provide a high speed, dynamic inspection for both surface-breaking defects as well as volumetric flaws in a single scan along the weld bead. There is no post-test cleanup or disposal required, the data is easy to interpret, and the test can be performed at elevated or high temperatures immediately after the weld is completed. Shipyard application of surface/volumetric weld inspection using EMATs has been evaluated in order to improve current methodology used for the surface and volumetric inspection of structure type welds. It is intended to overcome difficulties in conventional MT and liquid penetrant (PT) for surface inspection of welds and UT/RT for volumetric inspection of welds, and ultimately provide a higher quality, lower cost weld inspection technique. This work and previous projects have resulted in the following conclusions for surface inspection using EMATs:

- The EMAT surface wave test based on diffraction provides a good surface inspection technique for detection of surface-breaking/near-surface flaws in typical shipyard welds in the as-welded condition (no surface prep).

- The attenuation technique for surface inspection is useful for high speed scanning of mechanized welds. It is even more suitable for surface inspection of large areas of base metal at extremely high speeds. The test can even be used for painted surfaces.

- EMAT system portability/practicality is favorable, with the KAPL trip report stating that the EMAT system "was judged to be compact and practical for shipyard applications".

- Set-up times and test speeds were excellent, with the KAPL trip report stating "system set-up required less than one hour and the EMAT volumetric inspection speed was judged to be comparable to manual ultrasonic testing".

- The diffracted surface wave test speed is significantly faster than MT. The EMAT surface wave test was used to scan and mark indications on a 42' web-to-flange T-weld segment in seven minutes. It is estimated that this length of weld would have required approximately 100 minutes to inspect with MT.

Phased array EMATs proved to be best suited for the inspection of the volume of the weldment for both ship hull and piping welds. As a result of the work performed in this project and previous projects the following conclusions were obtained:

- It should be noted that all EMAT evaluations were conducted on as-welded surfaces, i.e., there was no surface preparation prior to EMAT testing.

- Phased array technology permits simultaneous surface/volumetric inspection of welds.

- Phased array technology provides not only the ability to detect flaws, but also allows complete weld characterization, i.e., it provides the capability to distinguish between significant flaws (LOF) and insignificant defects (scattered porosity).

- The incorporation of phased array technology offers enhanced performance capabilities for EMATs for weld inspection applications. Advantages include:

    - Excellent time-of-flight resolution for accurate velocity measurements

    - Removal of couplant influences for more accurate measurements (e.g., attenuation)

    - Generation of broadband signals more conducive to frequency analysis

    - High degree of signal reproducibility (derived from lack of couplant variations and reproducible transducer design and control) to enable application of feature extraction and pattern recognition algorithms or neural networks for classification of degradation

    - Enhanced scanning capability with limited probe movement requirements for applications involving complex geometries

    - Software control of focal spot size, depth, and angle, allowing for rapid scanning of many configurations

    - Ability to easily utilize any of the wave modes, including the SH wave mode, which is difficult to apply in a scanning mode with conventional UT

The results of the investigation into the design of EMAT instrumentation for portable applications in the shipyard indicate that it is possible today to build small, lightweight, portable EMAT instruments. In applications where permanent magnet based EMAT probes are used, the estimated weight of the EMAT instrumentation is 14 to 15 lbs. when using AC power, and 18 to 19 lbs. using a battery pack. In this design concept a visor-mounted display could be used for hands-free single man operation.

The areas where such systems would have the greatest impact are areas where the unique capabilities of EMATs provide advantages for non-destructive testing. Many of these EMAT inspection techniques have already been proven, both in the laboratory and in the field and are awaiting the development of low-cost portable instrumentation in order to be commercially viable. These areas of greatest impact for this development are expected to be:

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- Semiautomatic scanners and crawlers for thickness gauging and flaw detection applications, taking advantage of the ease of automation by eliminating the use of couplant using EMATs.

- Applications that take advantage of EMATs unique ability to utilize shear horizontal (SH) waves, Lamb waves, and Raleigh waves to perform inspections in a practical manner.

- Inspection applications for thickness gauging and flaw detection at elevated temperatures.

- Applications that take advantage of EMATs ability to electronically sweep the inspection beam I angle, such as the detection of defects oriented at random angles.

8.0 RECOMMENDATIONS

This work and previous projects have resulted in the following recommendations for weld inspection using EMATs:

Both EMAT surface inspection methods (diffraction and attenuation) are considered to be ready for shipyard implementation. Discussions with NAVSEA indicate that individual yards will be expected to make their cases for use of the technique for replacement of conventional surface inspection methods, e.g., MT and PT. In those cases where NAVSEA or applicable manufacturing code does not stipulate NDE requirements or prohibit the use of EMAT for surface inspection of welds/base metal, it is recommended that EMAT be pursued. There are commercial manufacturers of EMAT probes/electronics which can provide production systems, including spare parts, warranties, and service. MTI is prepared to assist the yards in implementation of the EMAT technology for surface inspection.

Positive results for the evaluation of phased array EMATs to inspect welds in magnetic steel piping warrant the further development of the technology and implementation of a shipyard system for inspecting these welds. The system would be of primary benefit in replacing manual ultrasonic testing of these welds, providing improved inspections at much faster scan rates, with computer documented results. The fully developed system would allow rapid reconfiguration for welds in piping of different diameter, thickness, and weld configuration. The next phase of development for this system should include the following tasks:

- Generate a specification covering pipe diameters, wall thickness, weld configurations, and types of defects to be used in defining the system. Also included in this specification should be scan rate, operating environment, calibration, and documentation requirements.

- Identify modifications to the system needed to be able to meet the specifications. These are expected to include the modification of the EMAT sensor and remote electronics to improve the sensitivity of the system and to field harden the system. In addition, software which would integrate control of the system with data processing and provide a user interface to take full advantage of the system's capabilities will likely be required.

- Incorporate the required modifications into the system and perform laboratory testing to verify the operation of the system.

- Transport the system to a shipyard and perform field trial inspections on actual piping welds.

- The results of the field trials would be used to guide the development of a commercial inspection unit.

The results for the evaluation of inspection of non-magnetic high-resistivity metals such as stainless steel, Inconel, and nickel copper alloys with phased array EMATs, indicate that these EMATs are not capable for providing defect through wall height measurement with adequate resolution to be useful in most shipyard piping weld inspections at the present time. If special circumstances are identified where conventional RT or UT are deemed inappropriate, and high through wall resolution is not required, then phased array EMAT inspections for these materials could be considered.

Positive results for the evaluation of a conceptual design of a small lightweight portable EMAT instrument for use in shipyard inspections warrant the further development and implementation of the instrument. The development of low-cost portable EMAT instrumentation could have widespread use for shipyard inspections and throughout industrial NDE. It is recommended that with the results of this conceptual design in mind, the most promising EMAT based shipyard inspections be identified, and detailed specifications for a portable EMAT instrument developed. Based on these specifications a portable EMAT instrument should be fabricated for use in shipyard testing trials. Improvements based on the results of the shipyard trials could then be incorporated in the production of commercial units.

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